LANDSCAPE FOREST MODELING OF THE LUQUILLO EXPERIMENTAL FOREST, PUERTO RICO

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This thesis contributes to modeling the dynamics of forest community response to environmental gradients and disturbances over a mountain landscape. A gap model (FACET) was parameterized for species of various forest types (Tabonuco, Colorado, Dwarf and Palm), for many terrain conditions and was modified and extended to include species response to excess soil moisture and hurricanes. Landscape cover types were defined by dominance of species of each forest type and canopy height. Parameters of the landscape model (MOSAIC) were calculated from multiple runs of FACET. These runs were determined by combining terrain variables (elevation and soil) and hurricane risk. MOSAIC runs were analyzed for distribution patterns. Geographic Information Systems software was used to process terrain variables, hurricane risk and MOSAIC model output.

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CHAPTER 1 INTRODUCTION

Luquillo Experimental Forest

The Luquillo Experimental Forest (LEF) is located in the Luquillo Mountains in eastern Puerto Rico. The LEF is congruent with the Caribbean National Forest, part of the USDA Forest Service National Forest System, and occupies 11,231 ha of land with elevations ranging from 100 to 1079 m above sea level (http://sunites.upr.clu.edu/sunceer/aboutluq/LEFSiteDescription.htm, 2001).

The LEF is a Long Term Ecological Research (LTER) site. LTER is a collaborative effort funded by the National Science Foundation (NSF) involving scientists and students investigating ecological processes over long temporal and broad spatial scales at many sites representing a variety of biomes and ecosystems (http://lternet.edu/, 2001). The LTER objectives for the LEF include long-term monitoring of environmental variables such as patterns of disturbance in space and time, ecosystem response to different patterns of disturbance, land-stream interactions, effect of management on ecosystem properties, and integration of ecosystem models and geographic information systems (http://sunites.upr.clu.edu/sunceer/aboutluq/LEFSiteDescription.htm, 2001).

Two main LEF study sites are El Verde and Bisley. The El Verde Field Station (EVFS) is part of the Institute for Tropical Ecosystem Studies (ITES) of the University of Puerto Rico at Río Piedras. The station is located on the western side of the LEF at N 18° 19’22", W 65° 49’13" and at 350 m of elevation above sea level (http://sunites.upr.clu.edu/sunceer/ aboutluq/LEFSiteDescription.htm, 2001). The Bisley research site is at 310 meters elevation and is located on the east side of the LEF. Meteorological data is gathered at both sites.

One of the LEF research programs to be expanded is the study of landscape dynamics. This includes expanding the comprehensive analysis of disturbance and ecosystem response to take into account the entire elevation gradient of the LEF and the different forest communities that occur along this gradient. This expansion also implies looking at factors that are important to the lower elevation forest and its response to disturbance and how it differs from higher elevations in forests where the climate is colder, wetter, and cloudier (LEF LTER proposal, 2000).

There are four main forest types in the LEF. Below 600 meters of elevation, the dominant forest type is the tabonuco (dominated by the species *Dacryodes excelsa*), which grows best on protected, well-drained ridges. Above 600 meters, the species palo colorado (*Cyrilla racemiflora*) is the dominant tree. On steep slopes or poorly drained soils, the palm *Prestoea montana* occurs in nearly pure stands. The Dwarf forest is occupied by short, small-diameter trees and shrubs. It is found on the highest ridges which are almost continually exposed to winds and clouds (LEF Web site 2001, Site Description).

Modeling

Computer models and simulations of ecological systems allow understanding of potential behavior under a variety of environmental conditions that would be too expensive or impractical to replicate in the real world environment. A model is a simplified representation of reality, based on concepts, hypotheses, and theories of how the real system works. A simplified view of the modeling methodology can be summarized in three stages.45

The first stage is the conceptual system description and problem definition. This stage looks at what questions are to be answered by the model, as well as verbal descriptions, assumptions, and questions. Next, biological, physical, and chemical (abiotic) components are defined. This also includes identifying the temporal and spatial scale of the model (e.g., number of years and size of area).

Designing the mathematical models and their simulation constitutes the second stage. A preliminary analysis is performed to determine existing relationships and how these can be quantified. Available data are used for calibration, parameter estimation and model evaluation.

Finally, the third stage is the analysis of the results obtained. Were the questions that motivated the development of the model answered? Also, are there any limiting factors to these answers? Then it must be decided what model modifications need to be completed, if any, or if the model can or should be extended (Acevedo, 2001).

Gap and Transition Models

The LEF landscape model project is based on building a landscape transition model from an individual-based model or gap model (Acevedo et al., 1995, 1996, 2001a, 2001b). The term “gap” refers to the space left when a tree dies and leaves an open area in the canopy. There is increased light in this space, and this affects which tree species grows in its place based on the species' preference for light. FACET is a gap model derived as a relief-sensitive version of the spatially-explicit ZELIG gap model (Urban et al., 1991, Urban and Shugart, 1992) (Dean L. Urban, FACET and ZELIG version 2, Department of Forest Sciences, Colorado State University, Fort Collins, CO 80523). FACET was used as the gap model for this thesis.

In FACET, regeneration, growth, and mortality are calculated tree by tree. Individual trees are competing for light, water and nutrients and are affected by temperature. Each species responds differently to the resources available and the surrounding environmental conditions. This program predicts forest development for a small parcel of land arranged in a grid made up of small plots. The size of the plots is scaled to the size of the largest trees so that the gap size corresponds to plot size.

MOSAIC is the transition model used in this thesis. MOSAIC is a semi-Markovian transition model (Dr. Miguel Acevedo, University of North Texas, Department of Geography, Denton, TX, 76203). A Markov model is based on probabilities that depend only on the current state. In a semi-Markov model, transitions also depend on holding time in the current state (Acevedo et al., 1995, 1996). The MOSAIC landscape model can be parameterized from FACET, which means the parameter values can be estimated by running FACET and using an automated parameterization program based on the SEMAPAR algorithm (Acevedo et al., 2001a). Geographic Information Systems (GIS) files hold the geographic information, such as soil type, elevation, slope, and aspect.

In MOSAIC, a collection of cells constitutes the landscape. Each cell is a mosaic of smaller, gap-size plots. The state of the cell equals the proportion of total area in each of several cover types. Therefore, the state variable of the landscape cell equals a vector that summarizes relative frequency of finer-scale elements within it. These elements are obtained by the most abundant species or cover type in each one of the smaller plots as calculated by the gap model. A current revision of MOSAIC includes interdependence among cells; in this case, each cell's state is partly dependent on the state of surrounding cells (Monticino et al., 2002).

Previous research to use FACET-MOSAIC scaling in tropical forests was conducted by Delgado (2000) for lowland tropical forests of the Imataca Forest Reserve in Venezuela. That model was derived for a very large area (about 10^6 hectares) and coarse spatial resolution (cell size of 500 meters x 500 meters) and employed 13 cover types based on species ecological role (defined by shade tolerance and tree height) as well as canopy height. The LEF MOSAIC model has been developed in this thesis for a smaller area (about 11,000 hectares) but at higher spatial resolution (cell size of 30 meters x 30 meters).

Motivation

There is increasing interest in managing forests over large areas with a sustainable long-term view. Computer models are very helpful to apply principles and theories of landscape ecology, and therefore provide guidance in environmental management (Acevedo et al., 2001b). Forest ecosystem management may benefit from the simulation of forest landscape dynamics under various management scenarios (Monticino et al., 2002).

As explained in a previous section, part of the LTER objectives include expansion of the research area to include the entire elevational gradient and the different forest communities that occur along this gradient. This thesis will help organize and make explicit postulated environmental factors and disturbances that control occurrence of forest types along this gradient and generate test hypotheses about which factors are important to the various forest types (LEF LTER Proposal, 2000).

Objectives

GENERAL

The purpose of this project is to simulate the landscape dynamics of the LEF in Puerto Rico using the MOSAIC model scaled up from a FACET model.

SPECIFIC

Calibrate and adapt FACET for the LEF. Specific objectives include:

Identify tree species to be included in the FACET simulations and calculate species-specific parameters.

Collect site information including precipitation, temperature, solar radiation, and soils in order to estimate site-specific parameters.

Modify FACET to approximate conditions in the LEF. Solar radiation, evapotranspiration, and leaf litter are all components that were not initially properly reflected in FACET for these conditions.

FACET must be extended to include the effects of hurricanes, soil water logging at higher elevations, and landslides.

Parameterize MOSAIC for the LEF. Identify terrain types to be used for MOSAIC parameterization.

Determine cover type to be used in MOSAIC.

Execute SEMAPAR to estimate the MOSAIC parameters for the entire area of the LEF.

MOSAIC simulation. Perform simulations and produce maps of predicted landscape dynamics for a variety of scenarios.

Methods

This section briefly describes the methods used and some of the results obtained.

CALIBRATE AND ADAPT FACET FOR THE LEF

The first step was to select the species to be included in the FACET simulations starting with species used in previous research efforts in the Tabonuco forest (Doyle, 1982, Pulliam and Parton, 1998). The list was completed using information from publications (http://www.southernregion.fs.fed.us/caribbean/resources.htm, 2001, Little and Wadsworth, 1964, Weaver, 1983) and by consulting LEF researchers. Especially important was the addition of Colorado and Dwarf forest species because of the initial lack of member species for each of these forest types. Once the species were identified, values for the individual species parameters were estimated using available information from the LEF. This process is explained and described in Chapter 2.

Site information from the LEF Web site was collected. This includes precipitation, temperature, and solar radiation data. Since the emphasis of this thesis is on landscape dynamics over an elevation gradient, an effort was made to describe variations of temperature and precipitation as a function of elevation. An existing soil survey (Huffaker, 1991) was used to collect soil information required by FACET, mainly wilting point, field capacity, fertility and depth. This process is described in Chapter 2.

The next step, described in Chapter 3, was to modify FACET to approximate the conditions in the LEF. At first, solar radiation and evapotranspiration were not properly reflected in FACET for LEF conditions. Thus, these components were modified to reflect LEF conditions.

Then, as described in Chapter 4, FACET was extended to include the effects of hurricanes and water logging, important factors in the LEF. FACET needs to reflect the ecological effects of a catastrophic, massive, and sudden tree mortality event (such as a hurricane) that contrast with those of local and gradual tree mortality in terms of the direction of succession after the event, community dynamics, and possibly selection of trees (Lugo and Scatena, 1996). Hurricane effects were incorporated in FACET using additional parameters: a site-specific parameter and a species-specific parameter. The site-specific parameter is a hurricane risk class (one to five, with five being the highest) associated with terrain position in the landscape and the species-specific parameter is a species susceptibility (one to five, with one being the most susceptible). Soil water logging was incorporated by generating an additional soil moisture stress factor estimated by number of wet days (defined as those days with soil water above field capacity).

Another possible modification of FACET for the LEF is the inclusion of landslides. The disturbance of landslides will not be added to FACET at this time, but may be added with further research at a later date.

FACET simulations were then conducted over a variety of terrain types, i.e., combinations of elevation, slope, aspect, soil type and hurricane risk class. These simulations are reported in Chapter 6 and analyzed to evaluate how well the results reflect the forest composition at different forest types.

PARAMETERIZE AND SIMULATE MOSAIC FOR THE LEF

The terrain type values used were determined using GIS maps (Chapter 5). Soil types were derived from GIS operations on soil mapping units and slope. FACET was then run over gradients of the various environmental factors (slope, elevation, and aspect) to reduce number of terrain types whenever possible. Parameters from FACET runs were used as input for SEMAPAR. These results are then input into MOSAIC to build up to the landscape level, which is the entire area of the LEF. Representative MOSAIC runs were made and maps generated for each run. This process is reported in Chapter 7.

Finally, Chapter 8 reports conclusions based on implementations and simulation results. The major implementation tasks achieved were the successful addition of upper-elevational species; input of site factors with the future requirement of more detailed soil data; a correction factor that made FACET's potential evapotranspiration (PET) calculation appear to be more correct; hurricanes successfully added with user-input hurricane frequencies, appropriate intensity factors, damage risk class based on location, and individual species susceptibility; soil water logging response added with future work necessary on model's sensitivity to soil moisture; terrain types identified that cause vegetation to respond and different forest cover types identified; and state based on canopy height and forest type with the future work of a different canopy height for each forest type.

Simulation results include both FACET and MOSAIC. In regards to FACET, representative species have basal areas comparable to observed field data, but overestimated. Successional patterns and long-term stand composition are compared to observed data. Simulation results from the final MOSAIC maps show the Colorado and Tabonuco forests appear to be dominating at the appropriate elevation ranges, while the Adaptive forests seem to be dominating some areas of the Dwarf forest elevation range (Dwarf forests only appear at the upper part of their elevation range), and Palm forests are not dominating in pure stands as the literature indicates they do (further research will determine the causes for this).

FLOWCHART

The flowchart shown in Figure 1-1 summarizes the LEF modeling process followed in this thesis. First, site and species information are used to run FACET at different elevations, number of years and terrain conditions. Then, results are compared to published data in the field. For instance, leaf area index (LAI) generated by FACET is compared to published values. If the values do not approximate observed conditions, then FACET is modified until approximate conditions are generated. For the LAI example, the allometric relationship in FACET may need to be modified for tropical species. The resulting stand composition modeled by FACET is compared to the known distributions in the LEF. For instance, predictions of forest types Tabonuco, Colorado and Dwarf at corresponding elevation ranges: 350 - 650, 650 - 900, and 900 - 1050 meters. Results reported in the literature are the main source of the data for comparison. Once the model qualitatively matches published data, FACET is extended to account for any local conditions, such as hurricanes for the LEF. Parameters from FACET runs are used as input for SEMAPAR.

Next, as shown in Figure 1-2, site terrain files are used to determine terrain types for SEMAPAR, which is then run over these different terrain types for MOSAIC parameter estimates. Transition probabilities and lags between each pair of states are determined.

Using these parameter values and topographical maps, MOSAIC is run over the entire landscape, as illustrated in Figure 1-3. MOSAIC landscape cells simulate changes in cover by considering transition probabilities and times to transition. These cells make up a landscape map of forest types. If the resulting MOSAIC maps look correct, then the maps are used to analyze the dynamics of cover-type transition. If the resulting maps do not appear as expected, then FACET and/or SEMAPAR are analyzed, modified, and re-run for input into MOSAIC. This process is repeated until satisfactory results are obtained.

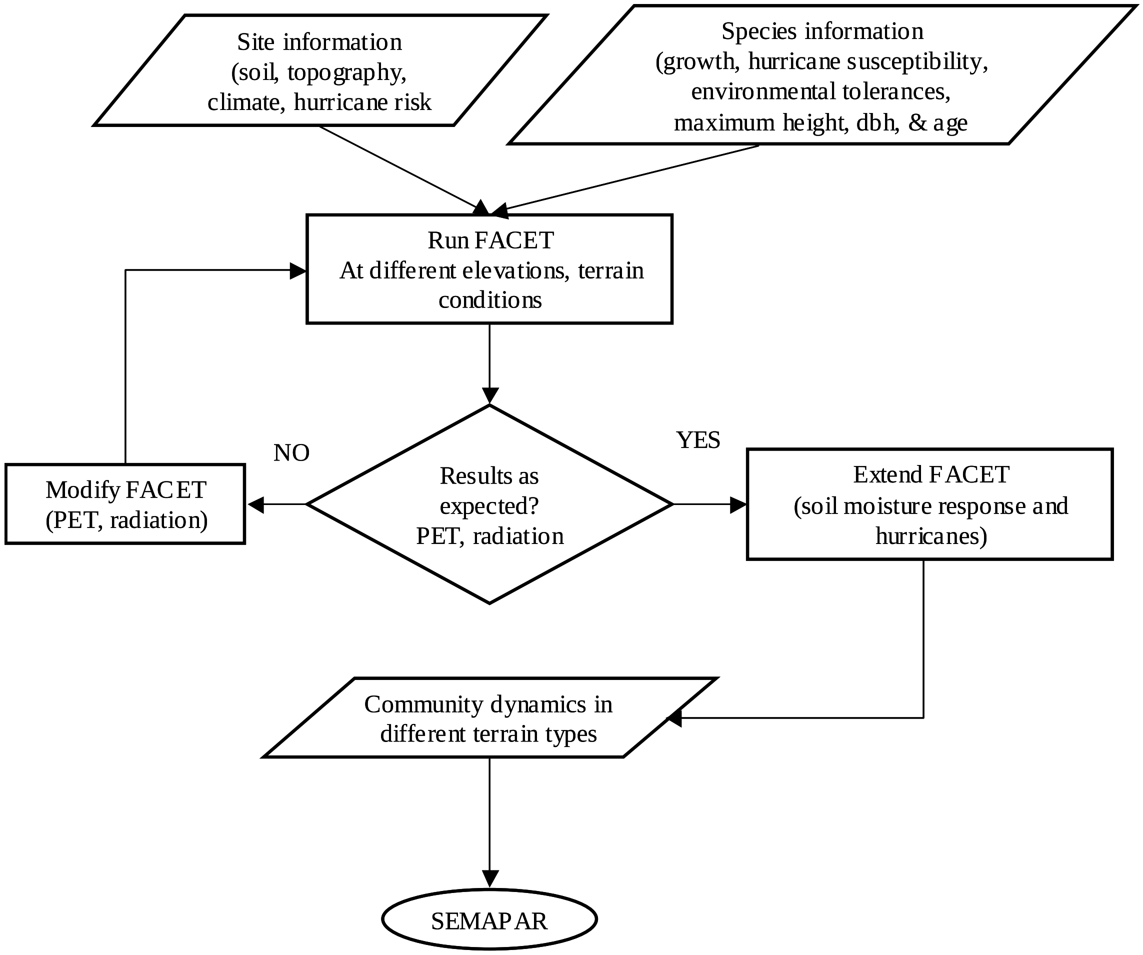

Figure 1-1 Flowchart of LEF FACET-MOSAIC Modeling Process

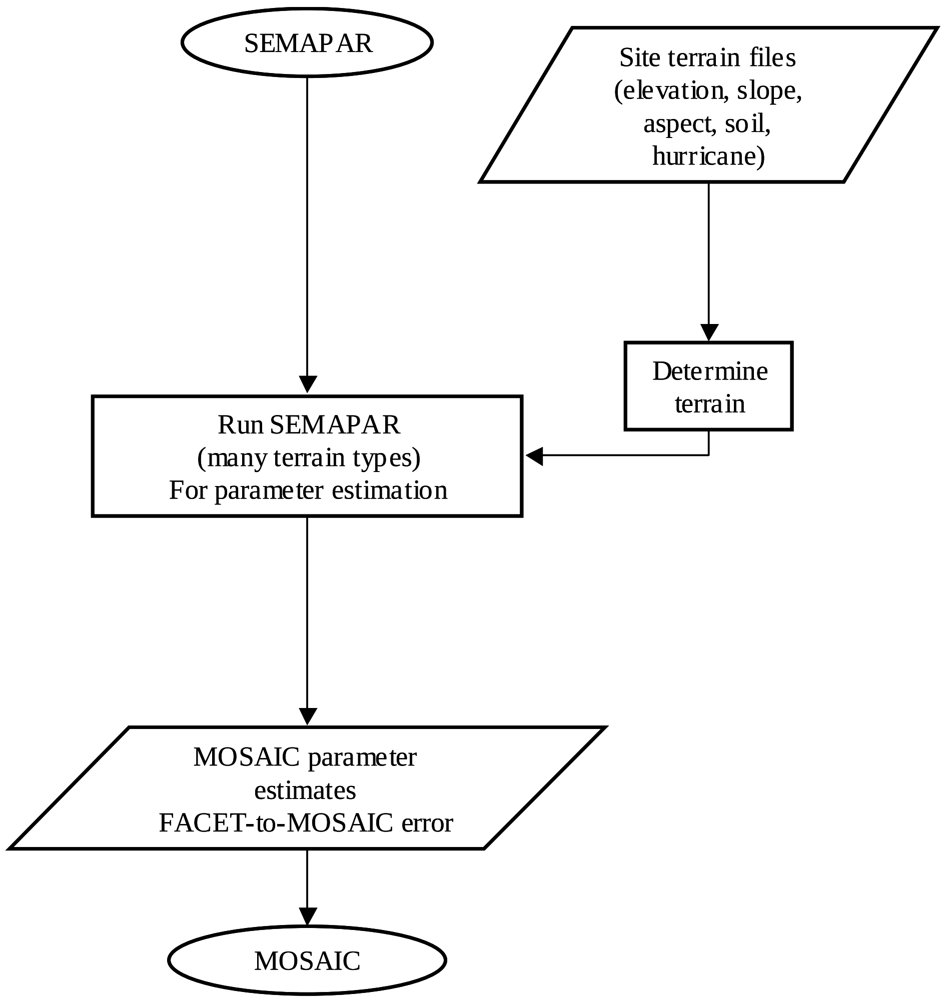

Figure 1-2 Flowchart of LEF SEMAPAR-MOSAIC Modeling Process

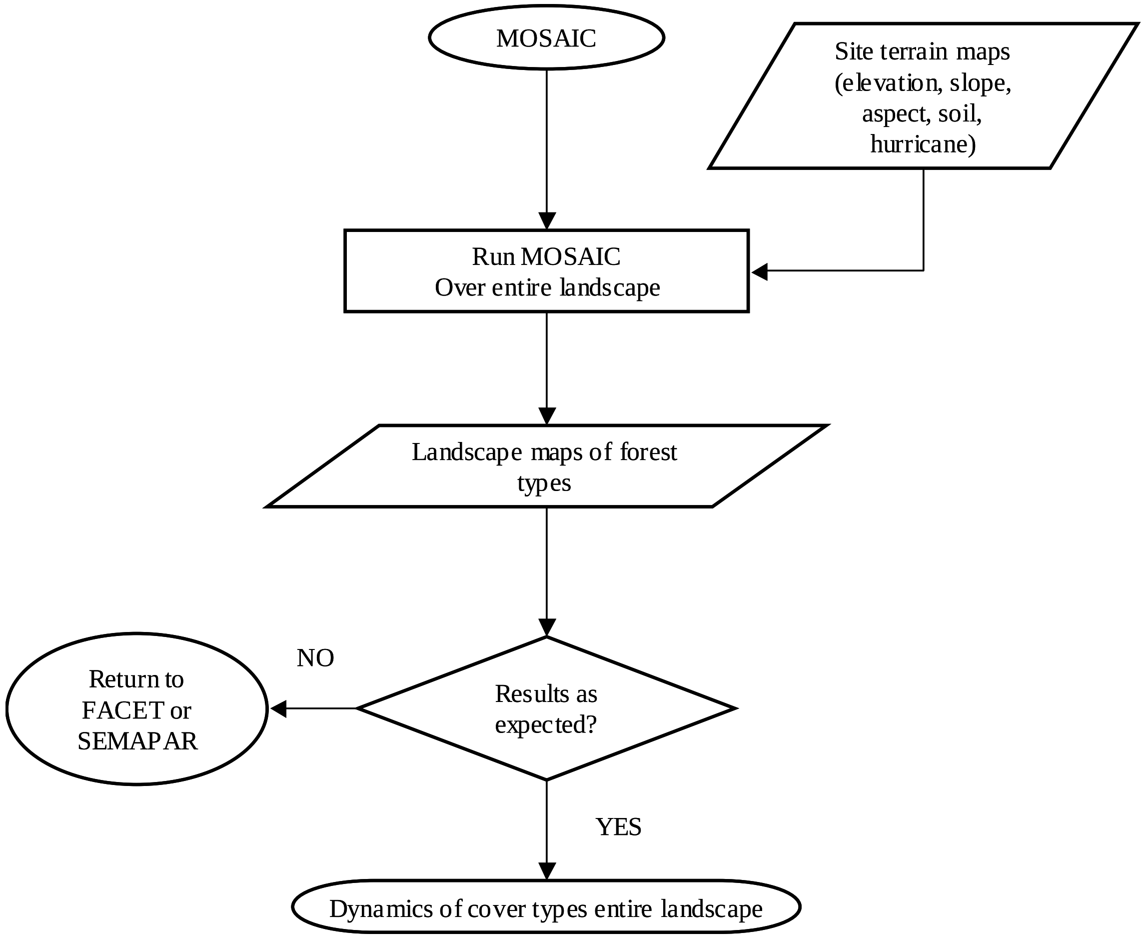

Figure 1-3 Flowchart of LEF MOSAIC Modeling Process

CHAPTER 2 FACET: LEF PARAMETER ESTIMATION

FACET: Species Parameters

SPECIES LIST

A species file was created for FACET. FACET is a gap model derived as a relief-sensitive version of the spatially-explicit ZELIG gap model (Urban et al., 1991, Urban and Shugart, 1992) (Dean L. Urban, FACET and ZELIG version 2, Department of Forest Sciences, Colorado State University, Fort Collins, CO 80523). This species file contains representatives for each of the four forest types in the LEF: Tabonuco, Palm, Colorado, and Dwarf. The starting species list for use by FACET included mostly Tabonuco forest type species and was assembled by Pulliam and Parton (1998) together with ZELIG gap-model parameter values. In Table 2-1, these species are listed together with a common name and elevation range obtained from Little and Wadsworth (1964). Some of the elevation ranges were modified to correspond with the results found in Weaver (1983).

Table 2-1Species List from Pulliam and Parton (1998) and Elevation Range Obtained from Little and Wadsworth (1964) and Weaver (1983)

Species Name	Common Name	Elevation Range
Cecropia schroeberiana	Yagrumo	200 m to 1050 m
Didymopanax morototoni	Yagrumo macho	200 m to 900 m
Casearia arborea	Rabo raton	Lower mountains
Inga laurina	Guamo	Lower mountains
Ocotea leucoxylon	Laurel geo	Colorado forest
Tabebuia heterophylla	Roble blanco	Lower mountains
Buchenavia capitata	Granadillo	Lower mountains
Cyrilla racemiflora	Colorado	Dominates at 600 – 900 m
Guarea guidonia	Guaraguao	Lower mountains
Manilkara bidendata	Ausubo	Lower mountains
Micropholis garcinaefolia	Caimitillo verde	Upper mountains
Prestoea montana	Palma	Dominates on steep slopes or poorly drained soils
Sloanea bertreriana	Motillo	Lower mountains
Dacryodes excelsa	Tabonuco	Dominates at 300 – 600 m

To identify possible additional species, lists used by Doyle (1986), the United States Forest Service Web site (http://www.southernregion.fs.fed.us/caribbean/resources.htm, 2001), and Little and Wadsworth (1964) were reviewed. These species were confirmed by Weaver (1983). A listing of these additional species together with elevation range can be found in Table 2-2.

Table 2-2 Additional LEF Species From USDA Web Site, Little & Wadsworth (1964), and Weaver (1983)

Scientific Name	Range (m)
Calycogonium squamulosum	600 – 1050
Cordia borinquensis	300 – 900
Daphnopsis philippiana	300 – 900
Miconia prasina	300 – 600
Miconia tetrandra	600 – 900
Psychotria berteriana	300 – 1050
Tabebuia rigida	> 900

SPECIES-SPECIFIC PARAMETERS

Parameter values are required for each species to be simulated. FACET parameters: maximum age, maximum diameter at breast height (dbh), maximum height, coefficients of diameter-height allometry, growth rate, life form, minimum and maximum growing degree-days, shade tolerance, drought tolerance, nutrient response class, seedling establishment rate, viable sprouting after mortality, and maximum diameter for viable stump sprouts. A list of the available values for each of the original species from Pulliam and Parton are given in Table 2-3.

Table 2-3 Original Species Parameters

Scientific Name	Max Age (yrs)	Max dbh (cm)	Max Height (m)	Growth Rate (mm^3/m^2 LAI yr^{-1})	Min Degree Days	Max Deg Days	Shade Toler. (Rank)	Drought Toler. (Rank)	Seed (Rank)
Cecropia schroeberiana	50	61	22	2000	3650	12045	1	3	10
Didymopanax morototoni	100	46	18	1000	5500	12045	1	2	3
Casearia arborea	150	15	9	1000	5000	12045	2	2	5
Inga laurina	100	46	22	1000	5000	12045	2	2	2
Ocotea leucoxylon	100	25	22	2000	5500	12045	2	2	3
Tabebuia heterophylla	150	46	17	1000	5500	12045	2	3	5
Buchenavia capitata	400	122	24	2500	5500	12045	3	2	2
Cyrilla racemiflora	2000	183	18	400	650	12045	3	1	2
Guarea guidonia	200	91	25	1000	5500	12045	3	2	2
Manilkara bidendata	400	122	31	800	3650	12045	4	2	3
Micropholis garcinaefolia	200	46	16	1000	3650	12045	4	1	5
Prestoea montana	200	20	23	50	3650	12045	5	1	3
Sloanea betreriana	200	91	30	700	5500	12045	5	1	3
Dacryodes excelsa	800	175	34	400	5500	12045	5	2	2

FACET uses the following relationship between tree height and diameter:

$$H_T = H_{\max} \times \left(1 - \exp\left(b_2 \times D\right)\right)^{b_3} \quad (2.1)$$

where:

H_T = tree height (m)
H_{max} = maximum tree height (m)
D = tree diameter (cm)
b_2,b_3 = allometric coefficients

During a simulation, FACET increments diameter according to a differential equation. Tree height is then determined from diameter using the above equation.

Diameter-height allometric coefficients for the original species in Table 2-3 were approximated from similar species occurring in other tropical forests (e.g., from Imataca and reported in Delgado, 2000). The values used are given in Table 2-5. These coefficients still need to be estimated by regression from data sets of diameter-height values of individual trees in the Tabonuco forest type which are not available at this time.

Even though this step was not completed for the original species (i.e., species in the Tabonuco forest type), coefficients of diameter-height allometric relationships were computed for the Colorado forest type species listed in Table 2-2 by regression from a collection of diameters and heights of individual trees covering a wide range of diameter values (data used was provided by IITF staff, Weaver, personal communication).

The results are shown in Table 2-4. *Tabebuia rigida* coefficients were estimated from Colorado forest species values by adjusting for elevational differences. As an example, the height-diameter relationship for the *Psychotria berteriana* is illustrated in Figure 2-1 (Please note that there is an outlier in this data that was not removed from the data as it appeared to be a valid measurement).

Table 2-4 Diameter-Height Allometric Coefficients for Additional Species

Scientific Name	b2	b3
Cordia borinquensis	-0.0722	0.77
Calycogonium squamulosum	-0.0354	0.519
Daphnopsis philippiana	-0.132	1.2
Miconia prasina	-0.127	1.83
Miconia tetranda	-0.0974	1.16
Psychotria berteriana	-0.26	1.1

Height-Diam relation for *Psychotria berteriana* Hmax = 8 b3 = 2.1 b2 = -0.26 Err = 17.78

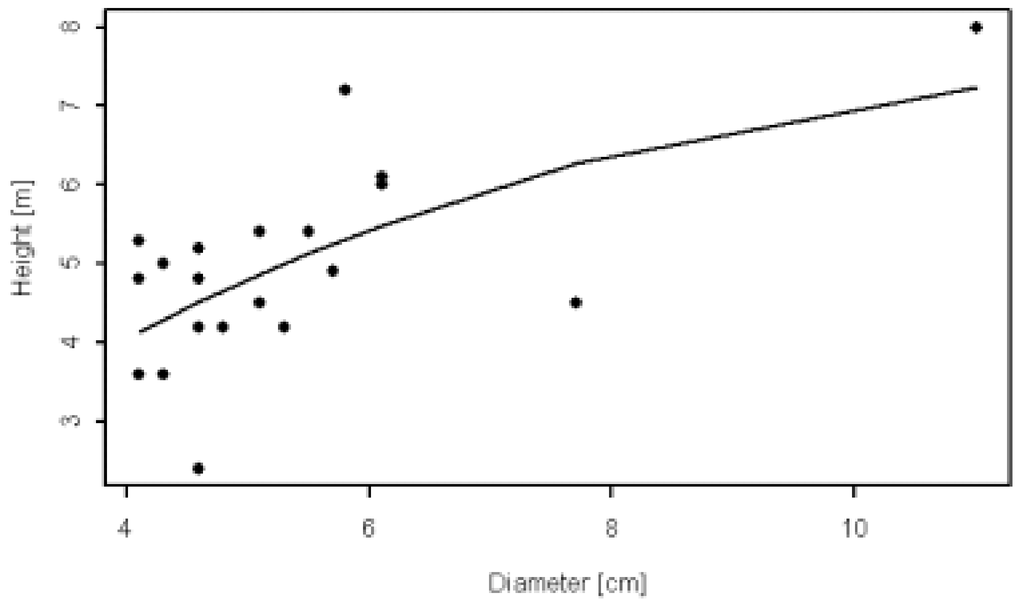

Figure 2-1 Example Height/Diameter Relationship

where:
b_3, b_2 = coefficients of diameter-height allometry

Minimum and maximum degree-days were adjusted by calculating degree-days corresponding to the temperature at the lowest and highest elevations where the species occur according to the ranges provided in Table 2-1 and Table 2-2. These adjusted values are reported in the resulting summary of species and parameters (Table 2-5).

Maximum dbh and height were estimated from available data in Weaver (1983). Growth rates were estimated from Weaver (1983) and adjusted to units used in FACET. Trees in a tropical moist forest do not have rings because of a continual growing season. For the additional species found in Table 2-2, maximum ages were educated guesses.

Other parameters for the additional species estimates were based on Weaver (1983). Table 2-5 contains a final list of all of the species included in FACET and their respective parameters except for additional parameters introduced as a consequence of extensions developed to adapt FACET to the LEF and reported later in Chapters 3 and 4 of this thesis. These species are grouped by the source of information used to estimate parameter values. For instance, all of the species parameters in Group 1 came from the same source. Sources are detailed in Table 2-6 for each of the groups by parameters.

Table 2-5 Combined Species List and Parameter Values

Scientific Name	Max Age (yrs)	Max dbh (cm)	Max Height (m)	b_2	b_3	Growth Rate (mm^3/m^2 LAI yr^{-1})	Min DD	Max DD	Shade Toler. (Rank)	Nutrient (Rank)	Seed (Rank)
Group 1											
Miconia prasina	800	18	15	-0.127	1.83	200	5000	7000	5	3	2
Cordia borinquensis	800	18	13	-0.0722	0.77	100	4800	5500	5	3	2
Daphnopsis philippiana	800	9	8	-0.132	1.2	100	4800	5500	5	3	2
Miconia tetranda	900	23	18	-0.0974	1.16	1000	4800	5500	5	3	2
Calycogonium squamulosum	800	22	12	-0.0354	0.519	100	1500	5300	5	3	2
Psychotria berteriana	800	11	8	-0.26	1.1	300	3650	10000	5	3	2
Group 2											
Casearia arborea	150	15	9	-0.0445	0.8	1000	5000	7000	2	3	5
Inga laurina	100	46	22	-0.0361	1	1000	5000	7000	2	3	2
Tabebuia heterophylla	150	46	17	-0.0808	1.6	1000	5000	7000	2	3	5
Buchenavia capitata	400	122	24	-0.03	1.2	2000	5000	7000	3	3	2
Guarea guidonia	200	91	25	-0.0404	1.2	1000	5000	7000	3	3	2
Manilkara bidendata	400	122	31	-0.029	1.2	800	5000	7000	4	3	3
Dacryodes excelsa	800	175	34	-0.0158	0.6	400	5000	7000	5	3	2
Didymopanax morototoni	100	46	18	-0.0573	1.4	1000	4800	7000	1	3	3
Ocotea leucoxylon	100	25	22	-0.0919	1	2000	4800	5500	2	3	3
Cyrilla racemiflora	2000	183	18	-0.0173	0.8	400	4800	5500	3	3	2
Micropholis garcinaefolia	200	46	16	-0.0316	1	1000	4800	5500	4	3	5
Sloanea betreriana	200	91	30	-0.0132	0.6	700	4800	5500	5	3	3
Group 3											
Tabebuia rigida	1000	14	7	-0.014	0.9	50	1500	5300	5	3	2
Group 4											
Prestoea Montana	200	20	23	-0.0515	1	50	3650	10000	5	3	3
Cecropia schroeberiana	50	61	22	-0.0419	0.8	2000	3650	10000	1	3	10

Table 2-6 Sources of Information by Group for Species' Parameter Values

Group	Max Age (yrs)	Max dbh (cm)	Max Height (m)	b_2, b_3	Growth Rate (mm^3/m^2 LAI yr^{-1})	Min, Max DD	Shade, Nutrient, Seeds
Group 1	Educated guess	Weaver, 1983	Weaver, 1983	Determined by regression	Weaver, 1983	Calculated	Educated guess
Group 2	Pulliam & Parton, 1998	Pulliam & Parton, 1998	Pulliam & Parton, 1998	Pulliam & Parton, 1998	Pulliam & Parton, 1998	Calculated	Pulliam & Parton, 1998
Group 3	Educated guess	Weaver, 1983	Weaver, 1983	Adjusted regression	Weaver, 1983	Calculated	Educated guess
Group 4	Pulliam & Parton, 1998	Pulliam & Parton, 1998	Pulliam & Parton, 1998	Pulliam & Parton, 1998	Pulliam & Parton, 1998	Pulliam & Parton, 1998	Pulliam & Parton, 1998

FACET: Site Parameters

TEMPERATURE

Monthly temperature data were obtained for EVFS, the El Verde Field Station (http://sunites.upr.clu.edu/sunceer/ DATA/lterdb16/data/ppttempsumavg.txt, 2001). These data contain maximum and minimum temperature for every month from January 1975 to present. From these data, the average minimum temperature and average maximum temperature were calculated, as well as a standard deviation for each. This was input into the FACET site file and is shown in Table 2-7 and Figure 2-2.

Table 2-7 Average Temperature Data for EVFS (all values in °C) Calculated From 1975-Present Data

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min	19	18.8	19	19.9	20.8	21.8	21.8	22	21.7	21.3	20.7	19.7
Max	23.5	23.8	24.7	25.8	26.5	27.3	27.1	27.3	27.2	26.3	24.8	24
Std Dev	0.6	0.7	0.7	0.8	0.8	0.6	0.6	0.6	0.6	0.7	0.7	0.9

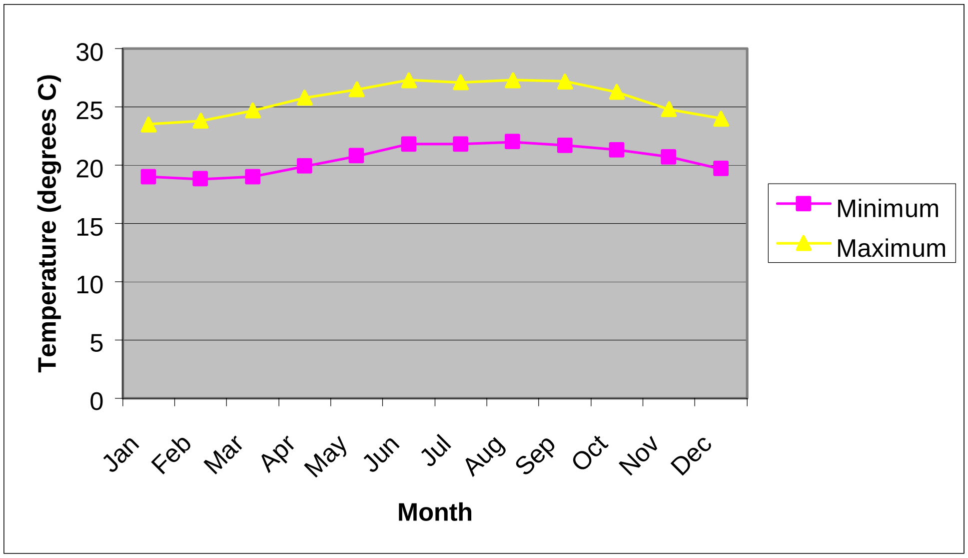

Figure 2-2 Average Temperature for EVFS Calculated From 1975-Present Data

The temperature lapse rates (i.e., change of temperature with elevation) are -0.6 °C per 100 m (at night time) and -0.9 °C per 100 m (during the daytime) (http://sunites.upr.clu.edu/sunceer/ DATA/lterdb16/data/ppttempsumavg.txt, 2001). These lapse rates were input into the FACET site file.

PRECIPITATION

Monthly precipitation data were also obtained for the EVFS. These data contains monthly precipitation from 1975 to present (http://sunites.upr.clu.edu/sunceer/DATA/lterdb16/data/ppttempsumavg.txt, 2001). The data were input and averaged for each month, and a standard deviation was determined. See Table 2-8 and Figure 2-3.

.

Table 2-8 EVFS Average Precipitation (cm) Obtained from 1975-Present Data Set

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Avg	23.3	22.7	19.8	22.9	35.2	24	30.2	36.6	34.7	28.2	39.6	34.8
Std Dev	9.9	12.6	13.5	12.1	13.5	10.8	11.8	15.3	17.3	15.4	19.7	23.2

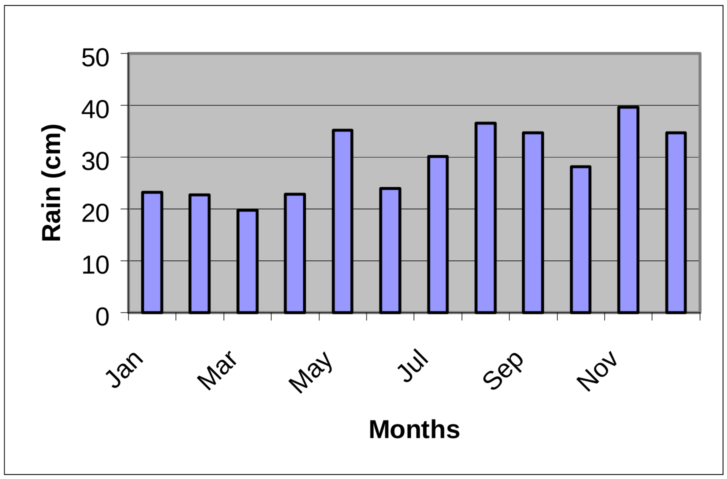

Figure 2-3 LEF Monthly Precipitation for EVFS from 1975 – Present Data

The LEF is considered a tropical rain forest climate as it is constantly moist and warm. This is illustrated in the climate diagram in Figure 2-4 which shows both the precipitation and temperature for the LEF.

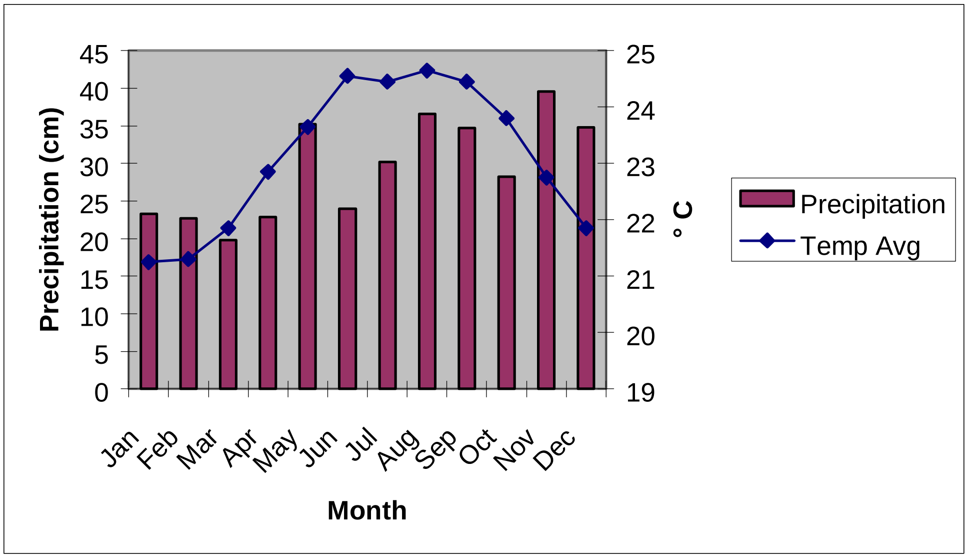

Figure 2-4 LEF Climate Diagram

As elevation increases, precipitation increases as well. To account for this increase, a formula was derived by Garcia et al. (1996) based on long-term rainfall data from the LEF, yielding relationships between rainfall and elevation.

This formula for annual precipitation based on elevation is non-linear:

$$R = 2300 + 3.8 \times E - 0.0016 \times E^2 \qquad (2.2)$$

where:

R = rainfall (mm)

E = elevation above sea level (m)

However, the FACET program uses a linear relation based on a change in elevation, not total elevation like in (2.2), and it yields rainfall difference with respect to base elevation for each month:

$$\Delta R = L \Delta E \qquad (2.3)$$

where:

ΔR = increment in rainfall due to change in elevation (cm)
L = rate of precipitation change (cm/m)
ΔE = change in elevation with respect to base (m)

To calculate a rate of change in precipitation based on change in elevation for FACET, a formula was derived based on change in elevation, rather than elevation like in Equation (2.2). To determine this new equation, a regression analysis was performed using precipitation as the dependent variable and change in elevation as the independent variable. Base elevation was assumed to be 350 meters, the approximate elevation of EVFS. The values for precipitation were calculated from Equation (2.2). The data are shown in Table 2-9 and the following formula resulted from the regression analysis:

$$R = 353 + 0.172\Delta E \qquad (2.4)$$

where:

R = annual rainfall (cm)
353 = estimated average rainfall for the base elevation (cm)
ΔE = difference in elevation from base (m)

This regression analysis had an $r^2 = 0.98$ showing a satisfactory fit of the linear rate of change to calculations by the Garcia et al. (1996) formula.

Equation (1.3) is in the same form as Equation (2.3), which is the one used in FACET. The actual rainfall for the base elevation is 360 cm, which is approximately equal to the estimated average rainfall for the base elevation in Equation (1.3). Therefore, the rate of change in precipitation to be used in the FACET equation is L= 0.172 cm/m.

Thus, 0.172 was input as the rate for change in precipitation in FACET. To test if this rate is correct, the expected precipitation was calculated based on the Garcia et al.

(1996) formula for elevations from 350 meters (base elevation) to 1050 meters (approximate highest altitude at LEF). Next, FACET was run at each of the above elevations for a 50-year time period. The precipitation totals for every 10 years were averaged, then compared to the LEF formula (see Table 2-9). (Note: The precipitation calculated by FACET fluctuates, increasing some years, but decreasing in others. This is due to the variability and randomness of precipitation values in FACET).

Table 2-9 Precipitation as a Function of Elevation

Elevation (m)	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**	**850**	**900**	**950**	**1050**
Formula precipitation[1] (cm)	343	356	369	380	391	400	409	418	425	432	437	442	447	453
FACET precipitation[2] (cm)	320	345	373	395	425	390	408	421	378	465	431	453	474	482
Difference (cm)	-23	-11	5	15	35	-11	-1	3	-47	34	-7	11	27	29

[1]From Garcia et al. (1996) formula
[2]From linear formula derived for FACET

See Figure 2-5 for a graphical illustration of this comparison between Garcia et al. (1996) and FACET formulas.

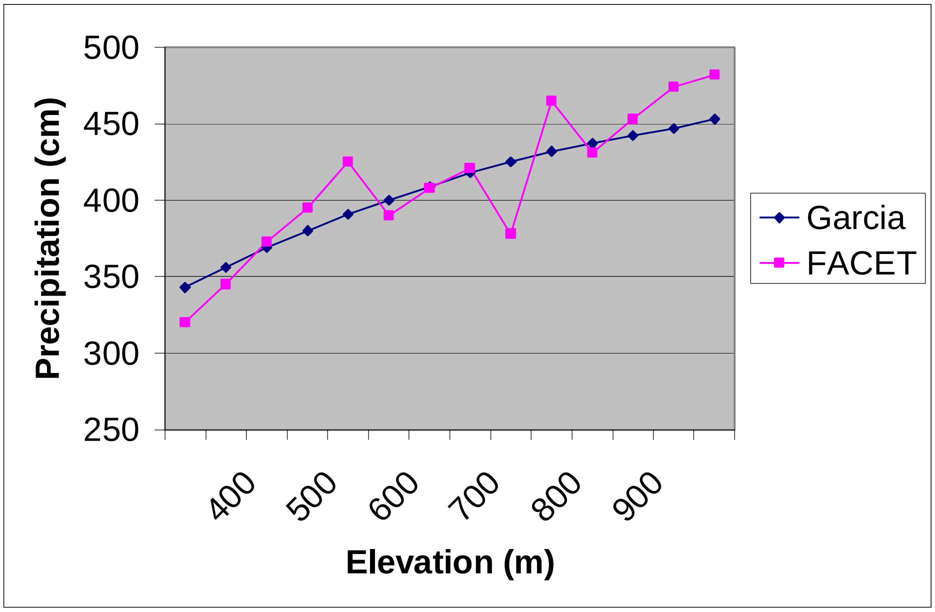

Figure 2-5 Comparison of FACET and Garcia et al. (1996) Precipitation Change with Elevation

As shown in Table 2-9, the average of all the differences between precipitation calculated by the Garcia et al. (1996) formula and the derived formula for FACET is 4. Based on this and as illustrated in Figure 2-5, the lapse rate of 0.172 appears to be working properly in the program.

SOLAR RADIATION

Obtaining Data. Solar radiation data were obtained for the Bisley research station (http://sunites.upr.clu.edu/sunceer/DATA/lterdb90/data/daily/bismetday98-00.txt, 2001). These data include the daily total solar radiation from 1998 – 2000 measured in watts/m^2. (Solar radiation data for El Verde was examined but was determined to be inadequate for this project.) Bisley data are incomplete with the days missing solar radiation data given in Table 2-10.

Table 2-10 Missing Radiation Data

Year	Julian Day(s) Missing	Calendar Day(s) Missing
1998	89	Mar 30
1998	90	Mar 31
1998	246	Sept 3
1999	136	May 16
1999	224	Aug 12
1999	271 – 277	Sept 28 – Oct 4
1999	327	Nov 23
2000	11 – 76	Jan 1 – Jan 11
2000	221 – 365	Aug 8 - Dec 31

A daily total average for this data were calculated. Then a monthly daily total average was calculated, and converted to calories/cm^2 for use in FACET (see Table 2-11).

Table 2-11 Bisley Solar Radiation

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1998 (w/m^2)	130	151	143	171	196	203	212	193	170	151	121	95
1999 (w/m^2)	125	156	206	208	233	176	178	190	191	129	105	100
2000 (w/m^2)				299	231	204	215					
Avg (w/m^2)	128	153	174	226	220	194	202	192	180	140	113	98
Avg (cal cm^{-2} day^{-1})	264	317	359	466	454	401	416	396	372	288	234	202

Comparing Data. To evaluate whether the data were reasonable, the above results were compared to San Juan solar radiation data (http://rredc.nrel.gov/solar/old_data/nsrdb/dsf/data/11641.txt, 2001). San Juan is approximately 30 miles northwest of the LEF at sea level. The San Juan data used are the average daily total solar radiation for the global horizontal elements (Wh/m^2) for 1961-1990. This data were converted to cal cm^{-2} day^{-1}. A direct, day-by-day comparison could not be performed, however, because San Juan hourly data are only available through 1990, and the LEF data available are based on 1998 – 2000. Instead, a comparison was done between the average computed in Table 2-11 for Bisley watershed data and the San Juan data. This comparison is shown numerically in Table 2-12, and illustrated graphically in Figure 2-6.

Table 2-12 Bisley/San Juan Solar Radiation Comparison

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Bisley (cal cm^{-2} day^{-1})	264	317	359	466	454	404	416	396	372	288	234	202
San Juan (cal cm^{-2} day^{-1})	368	423	492	525	497	521	524	513	476	423	371	340

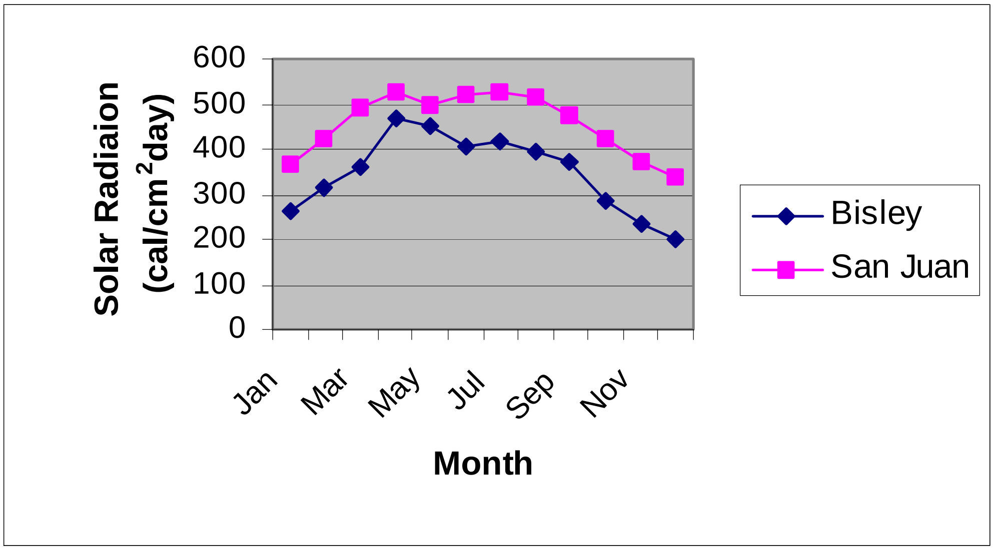

Figure 2-6 Bisley vs. San Juan Solar Radiation

The Bisley data appears reasonable because it increases and decreases consistently with the San Juan data, always remaining lower. This seems correct because rainfall and cloud coverage increases with elevation (Bisley is at a higher elevation than San Juan), which lowers solar radiation. The Bisley data were then used for input to FACET.

SOILS

Tree growth will depend in part on soil moisture and fertility. FACET can accommodate different soil types characterized by depth, fertility, fast flow fraction, field capacity and wilting point. These last two values related to soil texture can be input by layer.

Available Water. FACET computes available soil water for plant growth from field capacity and permanent wilting point. Field capacity is the amount of water in the soil at saturation; wilting point is the amount of water in the soil when it is insufficient and the plant wilts. Field capacity and wilting point were determined from texture (as percent of sand, silt and clay), which was determined from the LEF Soil Survey (Huffaker, 1991) and the Order 1 Soil Survey of the Luquillo Long-Term Ecological Research Grid, Puerto Rico (Soil Survey Staff, June 1995).

Percentages of sand, silt, and clay for 13 of the 18 LEF soil series were obtained from the soil survey. The other five soil series percentage of sand, silt, and clay were estimated by matching exactly the descriptions to existing layer compositions or to the closest description, or estimated (Christopherson, 2000, p. 531). These percentages were used to calculate the wilting point and field capacity in cm^3 H_20/cm^3 soil with the calculator provided on http://www.bsyse.wsu.edu/saxton/soilwater/ (2001).

In FACET, wilting point and field capacity per layer are scaled by layer thickness. See Table 2-13 for an example of this calculation for all of the layers of one of the soil series.

Table 2-13 Soil Field Capacity & Wilting Point Determination for Ciales Soil Series

Layer Description	Sand %[1]	Clay %[1]	Silt %[1]	Field Capacity (cm^3 H_2O/ cm^3 soil)[2]	Wilting Point (cm^3 H_2O/ cm^3 soil)[2]	Layer Depth (cm)[1]	Layer Field Capacity[3]	Layer Wilting Point[3]
Mucky clay loam/clay loam	34	28	38	0.2976	0.1573	23	6.84	3.62
Clay loam	53	29	18	0.2725	0.1683	17	4.63	2.86
Clay loam	51	30	19	0.2769	0.1709	24	6.65	4.10
Clay loam	64	14	22	0.2095	0.1065	27	5.66	2.88
Gravelly sandy loam	60	11	29	0.2079	0.0930	19	3.95	1.77
Clay loam	42	15	43	0.2465	0.1069	33	8.13	3.53
None	71	5	24	0.1689	0.0650	42	7.09	2.73
None	55	9	36	0.2125	0.0860	42	8.93	3.61

[1]Huffaker, 1991
[2]http://www.bsyse.wsu.edu/saxton/soilwater/, 2001
[3]Calculated values

See Appendix 1 for a listing of wilting point and field capacity for each soil series in the LEF.

Soil Fertility Indicators. FACET also requires a determination of soil fertility in Mg/(ha $\times$ yr) with a maximum fertility of over 20. To determine this soil fertility, three measurements are good indicators: cation exchange capacity (CEC), pH and organic matter (Barbour et al., 1998). In previous work to estimate fertility for FACET, effective depth and contents of coarse fragments have been used (Delgado, 2000).

CEC, the first indicator, is a measure of the number of negatively charged sites on soil particles that attract exchangeable cations. This allows the plant to uptake positively charged ions, and hence nutrients. One of the factors that influence CEC is clay content (Barbour et al., 1998). An additional soil fertility indicator, pH, does not greatly effect plant growth directly. However, an important indirect effect is its influence on nutrient availability and on microbial activity (Barbour et al., 1998, p. 490). Another good indicator, organic matter, is in the form of humus. This provides a long-term supply of continually available nutrients for plant growth. Effective depth is also a good indicator because it relates to space available to the trees for root growth and nourishment.

Obtaining Soil Fertility Indicator Measurements. Effective depth for each of the soil series was taken directly from the soil survey. CEC was only listed in the soil surveys for 13 of the 18 soil series. For the five remaining soil series, CEC was estimated based on soil descriptions of other soil series. The other indicators (pH, organic matter, and contents of coarse fragments) are not available in the soil surveys.

Because the only currently available factors in the soil survey are effective depth and CEC, these were used to estimate preliminary soil fertility factors for FACET. Effective depth was assigned an index value based on the depth ranges found in Table 2-14.

Table 2-14 Effective Depth Ranges

Index	Depth (cm)
5	201 – 250
4	151 – 200
3	101 – 150
2	51 – 100
1	0 – 50

The “better” (in this case deeper) the depth value, the higher the index value.

The CEC was either given in the soil survey by layer or estimated by layer. Each layer has a different depth. Therefore, the CEC was multiplied times the layer depth to obtain a weighed average CEC. Next, the CEC was assigned an index value based on the ranges of CEC weighted averages found in Table 2-15.

Table 2-15 CEC Index Values

CEC Index	CEC Range
5	1.00+
4	0.75 – 0.99
3	0.50 – 0.74
2	0.25 – 0.49
1	0.01 – 0.24

Again, the “better” (in this case higher) the CEC value, the higher the index value. Thus, a higher index value indicates a correspondingly higher CEC range.

Next, a fertility ranking was assigned based on the two index values of effective depth and CEC, as shown in Table 2-16. CEC and effective depth were equally important in ranking the soil types relative to each other for purposes of species response in FACET but not an absolute estimate of soil fertility.

Table 2-16 Fertility Ranking Determination

Depth Index	CEC Index	Fertility Ranking
1	1	12
1	2	13
1	3	14
1	4	15
1	5	16
2	1	13
2	2	14
2	3	15
2	4	16
2	5	17
3	1	14
3	2	15
3	3	16
3	4	17
3	5	18
4	1	15
4	2	16
4	3	17
4	4	18
4	5	19
5	1	16
5	2	17
5	3	18
5	4	19
5	5	20

An example of soil fertility determination follows for the Utuado soil series. This soil series has a medium-depth soil of 127 cm, resulting in an effective depth index of three. It has a high weighted average CEC of 2.99, which gives it a CEC index of five. From the lookup table, the resulting fertility is 18 (no units because this is a relative, not absolute, measurement). Based on these calculations, this is one of the most fertile soil series in the LEF (details given in Table 2-17). See Table 2-18 for each soil series' effective depth, CEC, and fertility measurement.

Table 2-17 FACET Fertility Factor for Utuado Soil Series

Layer Description	Layer Depth (cm)	Soil Series Effective Depth	Effective Depth Index	Cation Exchange Capacity (CEC)	CEC x Layer Depth	Weighted Avg CEC	CEC Index	FACET Fertility Factor [Mg/ (ha×yr)]
Sandy loam	3			0.91	2.73			
Sandy loam	12			0.61	7.32			
Sandy loam	15			0.48	7.20			
Sandy loam/ loamy sand saprolite	39			2.96	115.44			
Loamy sand saprolite	58			4.27	247.66			
Total soil		127	3		380.35	2.99	5	18

Table 2-18 Individual Soil Series Relative Fertility Factors

Soil Series	Effective Depth	Effective Depth Index	CEC	CEC Index	Relative Fertility Factor
Ciales	182	4	1.10	5	19
Dwarf	153	4	1.00	5	19
Humatas	190	4	0.25	2	16
Los Guineos	237	5	0.24	1	16
Moteado	133	3	0.18	1	14
Palm	144	3	0.69	3	16
Picacho	145	3	0.51	3	16
Utuado	127	3	2.99	5	18
Yunque	150	3	0.19	1	14
Zarzal	230	5	0.34	2	17
Cristal	116	3	0.29	2	15
Prieto	125	3	0.69	3	16
Coloso	125	3	0.62	3	16
Cagaubo	28	1	0.33	2	13
Guayabota	36	1	0.39	2	13
Icacos	152	4	0.48	2	16
Mucara	53	2	0.22	1	13
Plata	152	4	0.23	1	15

In this thesis, species-specific parameter values as a response to soil fertility have not been determined due to lack of complete information. Thus, this parameter was set to a neutral value for all species and the species will not respond differently to soil fertility in all simulations performed in this thesis. Future work should address determining species-specific response to soil fertility.

A fertility indicator unique to tropical rainforests is leaf litter. All primary and most other nutrients have maximum availability in the pH range of 6.0 – 7.5 (Young, 1976, p. 299), but a lot of soils in the LEF are acidic. Thus, trees in a tropical rainforest obtain a lot of nutrients directly from leaf litter. No additional work on leaf litter was done in this thesis but should be addressed in future work.

Fast-Flow Fraction. Another required soil parameter for FACET is fast-flow fraction (FFF). This is the percentage of water infiltrating the soil that flows quickly through the various layers. The lower the clay percentage (and consequently the higher the sand and silt percentage), the quicker the water will flow. So, to determine this fraction, the clay percentage for each soil series was taken from the soil survey.

The range of clay percentages for the LEF soil series is 6 – 59 %. The range of FFF for FACET is up to 20% (an FFF of 20% indicates a larger amount of water will flow through quicker than an FFF of say 10%). The soil with the lowest percentage of clay is Utuado at 6%. This soil series was used to determine a scaling factor by dividing 20 percent (the maximum FFF in FACET) by 94 (the sand and silt percentage of this soil) for a factor of 0.2128. This factor was multiplied times each soil series' percentage of sand and silt to determine an FFF. For example, 83% of the Picacho soil series is sand and silt. This is scaled to an FFF of 18% by multiplying by 0.2128. See Table 2-19 for the Picacho example and Table 2-20 for all soil series' clay percentage and FFF.

Table 2-19 Fast-Flow Fraction Picacho Soil Series

Layer Description	% Clay	Layer Depth (cm)	Effective Depth (cm)	Weighted Clay	Wtd Avg Clay	Wtd Avg Sand & Silt	FFF Scaled to 20%
Sandy loam	18.6	3		56			
Sandy clay loam	20.2	15		303			
Sandy clay loam	20.5	12		246			
Sandy clay loam	22.6	30		678			
Gravelly loam /sandy loam	14.6	85		1,241			
			145	2,524	17	83	0.18

Table 2-20 Clay % and Fast Flow Fraction

Type	Clay %	FFF
Ciales	19%	0.17
Dwarf	30%	0.15
Humatas	32%	0.14
Los Guineos	43%	0.12
Moteado	59%	0.09
Palm	36%	0.14
Picacho	17%	0.18
Utuado	6%	0.20
Yunque	52%	0.10
Zarzal	45%	0.12
Cristal	57%	0.09
Prieto	43%	0.12
Coloso	44%	0.12
Cagaubo	30%	0.15
Guayabota	35%	0.14
Icacos	40%	0.13
Mucara	58%	0.09
Plata	57%	0.09

Conclusions

We started with a FACET species file containing 14 species, mostly from the Tabonuco forest type. Seven additional upper elevational species were successfully added, including a Dwarf forest species (*Tabebuia rigida*). For these additional species, maximum diameter, age, and growth rate were estimated from published data. Minimum and maximum degree-days were determined using the lowest and highest elevations where the species occur. Diameter-height allometric coefficients were determined by a regression using data of individual trees for the Colorado forest. This process needs to be done in the future for the Tabonuco species. Due to lack of information about species response to soil fertility, this parameter was assigned the same value for all species. Further research is required to estimate better values for the nutrient response parameter.

For the FACET site file, monthly temperature, precipitation, and solar radiation data were obtained and appear reasonable when compared with available data. FACET's rate of change of precipitation with elevation was successfully calculated.

Thirteen of eighteen soil types had measurements available to estimate soil moisture parameters and fertility. Percent sand, clay, and silt were used to determine field capacity and wilting point by layer. For soil fertility, organic matter, pH, and contents of coarse fragments were not currently available. However, all but five soil types had effective depth and CEC data, which were assigned a combined index value and ranked. The remaining five soil types were assigned soil moisture and fertility measurements by matching soil descriptions to the appropriate soil type. Fast-flow fraction was determined from the clay percentage for each soil series and scaled for

FACET. Further work is required to obtain more soil data to better estimate soil fertility and utilize FACET's ability to accommodate species' response to soil fertility.

CHAPTER 3 MODIFY FACET FOR THE LEF

Solar Radiation

Many gap models require input of solar radiation data in the site file. FACET, a gap model derived as a relief-sensitive version of the spatially-explicit ZELIG gap model (Urban et al., 1991, Urban and Shugart, 1992) (Dean L. Urban, FACET and ZELIG version 2, Department of Forest Sciences, Colorado State University, Fort Collins, CO 80523), can calculate solar radiation using the Nikolov and Zeller (1992) model and adjusting for slope and aspect using standard geometric models. In previous work using FACET for tropical forests (Delgado, 2000), FACET-generated solar radiation was found to be underestimated with respect to field data. Therefore, a switch was introduced in FACET to turn this solar radiation model on or off, allowing the program to compute solar radiation internally or alternatively to directly use radiation data entered in the site file.

A test was performed for the LEF. The program-computed solar radiation appeared to overestimate solar radiation data for the Bisley site (see Table 3-1and Figure 3-1). Therefore, the program was used with radiation data switch set to off, so the program used the Bisley radiation data input into the site file.

Table 3-1 FACET Solar Radiation Model Test for LEF

Month	J	F	M	A	M	J	J	A	S	O	N	D
FACET solar model on (cal/cm^2 day)	355	407	469	505	503	527	512	492	463	419	352	334
Bisley solar radiation data (cal/cm^2 day)	264	317	359	466	454	401	416	396	372	288	234	202

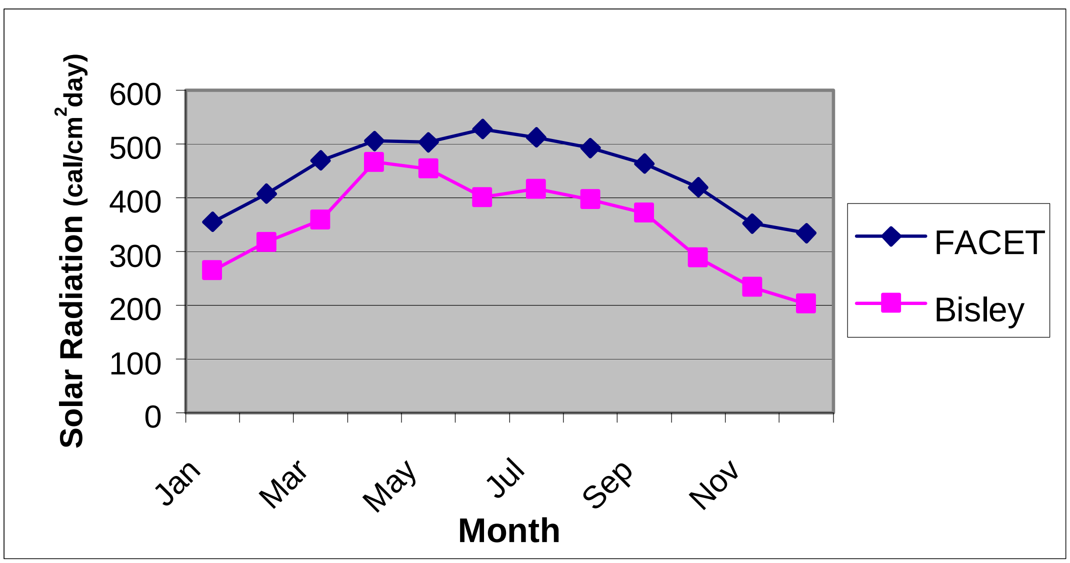

Figure 3-1 FACET Solar Radiation vs. Bisley Data

Evapotranspiration

Evaporation and plant transpiration are the two components of evapotranspiration (ET). The maximum value of ET achieved when there is no limit of soil moisture for plant transpiration is referred to as potential evapotranspiration (PET), whereas the actual amount of ET restricted by soil water is actual evapotranspiration (AET). PET is driven by two factors: radiative (controlled by temperature and radiation) and advective (controlled by relative humidity and wind).

UNDERESTIMATION OF PET FOR LEF

FACET calculates total PET to be around 90 cm/year at the elevation of 350 meters at LEF. At this same elevation, PET should be around 144 cm/year according to the LEF Website (http://sunites.upr.clu.edu/sunceer/aboutluq/ LEFSiteDescription.htm) or even higher at around 200 cm/year according to a recent study (Shellekens et al., 2000, p. 2183). Thus, FACET appears to be underestimating PET for the LEF.

To calculate PET, FACET uses solar radiation and temperature to compute the heat equivalent of PET using the Priestley-Taylor approximation and to convert heat to water by dividing by the latent heat of vaporization. This is accomplished using the following equations:

$$hvap = 597.31 - 0.568 \times T_a \qquad (3.1)$$

$$h = ct \times (T_a - tx) \times R_s \qquad (3.2)$$

$$p = \frac{h}{hvap} \times \frac{days(mo)}{ts} \qquad (3.3)$$

where:

p = PET (cm)
h = heat equivalent of PET cal $cm^{-2}day^{-1}$
$hvap$ = latent heat of vaporization cal cm^{-3}
T_a = mean monthly temperature (° C)
R_s = mean monthly solar radiation (cal cm^{-2} day^{-1})
ct = constant 0.01318
tx = constant –4.461
ts = 16 (number of timesteps)
$days(mo)$ = days in month mo

PET is then calculated each month and then totaled for the year.

After determining PET, FACET subtracts out the evaporation component in order to use the remaining water for soil water balance. Part of the evaporation occurs at the canopy level, so FACET computes an amount of precipitation intercepted by tree leaves. This is estimated by multiplying a percentage of 0.05 times the leaf area index (LAI). Initially, when FACET was run for 900 years at an elevation of 350 meters, the LAI was at most around one, resulting in an interception of approximately 5% (0.05 times one).

According to a recent study in the LEF, the throughfall/precipitation ratio should be between 45 – 70% (Schellekens et al., 2000, p. 2191). Based on this statistic, the interception should then be 30 – 55%. So FACET was also underestimating interception for the LEF.

The average LAI for the Tabonuco forest is between 6 and 7 (Shellekens et al., 2000, p. 2185) and this interception should be approximately two-thirds of ET (Schellekens et al., 2000, p. 2183), but FACET is only currently computing leaf interception at around 10% of ET. In the next section, investigation into why PET is not properly calculated for the LEF is discussed as well as the adjustment made to properly reflect this parameter.

FACET: PET CALCULATION UNDERLYING LOGIC

FACET PET calculation is based on Bonan (1989). To determine why FACET is underestimating PET, this article was examined. Basically, the Bonan formulation simplifies the Priestley-Taylor equation by assuming that the soil heat flux is equal to zero when averaged over several days and that the net radiant flux is proportional to solar irradiance and air temperature, resulting in the following equation:

$$E_p = a(T_a + b)R_s \qquad (3.4)$$

where:

E_p = mean monthly potential evapotranspiration (cal cm^{-2} day^{-1})
a,b = empirically derived site constants
R_s = mean monthly solar radiation (cal cm^{-2} day^{-1})
T_a = mean monthly temperature (° C)

The site specific constants a,b are calculated as follows:

$$a = \left[38 - \frac{2E}{305} + \frac{380}{e_2 - e_1}\right]^{-1} \qquad (3.5)$$

$$b = 2.5 + 0.14(e_2 - e_1) + \frac{E}{550} \qquad (3.6)$$

where:

E = site elevation in meters

e_2 , e_1 = saturation vapor pressures (mbar) at the mean max and mean min daily temperatures, respectively, of the warmest month of the year

The saturation vapor pressures are calculated from air temperatures using the following approximation from Bonan (1989):

$$e_s = 33.8639\left[\left(0.00738 \times T_a + 0.8702\right)^8 - 0.000019 \times \left|1.8 \times T_a + 48\right| + 0.001316\right] \qquad (3.7)$$

See Table 3-2 for an illustration of how the Bonan formula is applied. In this table we calculate an approximation of January's PET.

Table 3-2 January LEF Mean Monthly PET Using Bonan

$E_p = a(T_a + b)R_s$
$E_p = 98.33$ cal/(cm^2 day)
$T_a = 23.175$
$R_s = 264$
$a = [38 - (2E/305) + 380/(e_2 - e_1)]^{-1}$
$a = 0.013452$
$b = 2.5 + 0.14(e_2 - e_1) + E/550$
$b = 4.51$
$E = 350$
$e_s = 33.8639[(0.00738T_a + 0.8702)^8 - 0.000019\|1.8T_a + 48\| + 0.001316]$
$e_1 = 36.27$
$e_2 = 26.43$

PET calculated in Table 3-2 for LEF was 98 cal/(cm^2 day), which when converted from this energy form to water for the entire year, approximates 90 cm/year, substantially below measured evapotranspiration in the LEF.

A more complete method of determining PET is the Penman-Monteith method because it includes both radiative and advective components. However, even this method underestimates PET in the LEF (Schellekens et al., 2000). The FACET program needs to be changed to generate more accurate evapotranspiration amounts for the LEF.

Part of the problem with using the Priestley-Taylor method is that this uses monthly temperature and solar radiation averages. In actuality, there are many short rains and sunny periods that result in more evaporation than the average values suggest (Scatena, personal communication). Another one of the reasons evapotranspiration is higher in the LEF is due to wind advection because of the proximity of the Atlantic Ocean. To compensate for the underestimation we simply used a scale factor of 1.75 that was multiplied times the site-specific constant "a". This scale factor was based on trial-and-error. After including this multiplier, PET generated by FACET now approximates the LEF values reported in the LEF Website (http://sunites.upr.clu.edu/sunceer/aboutluq/LEFSiteDescription.htm, 2001) all along the elevational gradient, as seen in Table 3-3.

Table 3-3 Adjusted PET Values (mm/month)

Forest Type	FACET Average	LEF Average
Tabonuco	123	120
Colorado	100	100
Dwarf	78	80

Conclusions

Solar radiation was overestimated by FACET. Thus, the program was set to directly use the Bisley radiation data input into the site file. PET was underestimated by FACET, so it was determined that a correction factor should be added. After adding this factor, PET results match those measured for the LEF.

CHAPTER 4 EXTEND FACET FOR THE LEF

Incorporating the Effects of Hurricanes in FACET

The effects of hurricanes were added to the FACET program. FACET is a gap model derived as a relief-sensitive version of the spatially-explicit ZELIG gap model (Urban et al., 1991, Urban and Shugart, 1992) (Dean L. Urban, FACET and ZELIG version 2, Department of Forest Sciences, Colorado State University, Fort Collins, CO 80523). Determining an appropriate recurrence timeframe was one of the first steps in adding this disturbance type. Then hurricane intensity was determined from hurricane category. Next, a damage risk class was used for each topographical location. Finally, species susceptibility was used to determine mortality by species.

FREQUENCY

Research indicates that every 50-60 years LEF is affected by hurricane, and that the Tabonuco forest is in a continuous state of recovery from disturbances (Vogt et al., 1996). Historical records show that a hurricane passes over Puerto Rico about once every nine years (Doyle, 1982). To accommodate for uncertainty in the frequency, the FACET modification was made based on a uniform distribution for the interval [min, max] where min and max are minimum and maximum hurricane recurrence time.

A uniform distribution was used due to lack of better data on hurricane frequency. An improvement of the above formulation would be to use a different probability density function (PDF) for hurricane frequency. This could be investigated during future work with better statistics on hurricane frequency.

INTENSITY

During a FACET simulation, the program checks to determine if the time to next hurricane has elapsed. If so, the program will randomly generate the hurricane category on a scale of 1 to 5 that corresponds to the Saffir-Simpson Hurricane Damage Potential Scale shown in Table 4-1 (Christopherson, 2000). However, the probabilities of a given hurricane being in an individual category are not equal. However, in the absence of a specific PDF for hurricane intensities, this thesis will not assign different probabilities to each of the five categories.

According to a recent study, a Category 1 hurricane level results in approximately 70% of the trees being damaged (Francis and Gillespie, 1993). At Category 2 and above, 80% of the trees are damaged (Francis and Gillespie, 1993). Once a storm reaches Category 2, the variability of damage is due to factors other than wind speed. Those factors include individual wind gusts (pulses of wind can cause more damage than a steady wind), precipitation (Everham, 1996), and species susceptibility (Francis and Gillespie, 1993). Based on this research, the intensity factor is assigned that corresponds to the respective hurricane category (also found in Table 4-1.)

Table 4-1 Saffir-Simpson Hurricane Categories and Corresponding Assigned Intensity

Category	Wind Speed (mph)	Wind Speed (kmh)	Intensity
1	74 – 95	118-152	0.7
2	96 – 110	153-176	0.8
3	111 – 130	177-208	0.8
4	131 – 155	209-248	0.8
5	> 155	>248	0.8

In this thesis, hurricane time for recurrence was made independent of intensity. Clearly, higher intensity hurricanes would have longer recurrence time than lower-intensity storms. A sliding scale of recurrence time linked to intensity could be designed in future work.

After assigning this intensity factor to each category, a multiplier is determined on an ad-hoc basis from rain and wind gust because of the formerly mentioned evidence that these are critical factors in a hurricane. These multipliers are given in Table 4-2 and will be used to modify the intensity damage factor. These values are just educated guesses and need to be analyzed by sensitivity analysis and revised in future work.

An example calculation follows. If the hurricane is a Category 3, the intensity factor from Table 4-1 is 0.8. If the amount of rain is high and the wind gusts are low, the multiplier from Table 4-2 is 1.1. This will be multiplied times the intensity factor for a resulting intensity factor of 0.88. This value will be assigned to a variable I, intensity of hurricane that will be used later to calculate percentage blowdown.

Table 4-2 Rain/Gust Multipliers

Rain	Gust	Multiplier
Low	Low	1.0
High	Low	1.1
Low	High	1.1
High	High	1.2

Mortality due to a hurricane tends to be low as severely damaged trees often recover, even though their structural damage may be high. In the tropics especially, a blowdown as opposed to a death is more likely to occur during a hurricane. Research shows that percent resprouted stems may be as high as 64.8% of dicot stems, 87% of snapped stems, or 56% of all trees in the tropics (Everham, 1996).

DAMAGE RISK CLASS

The next step is to assign a damage risk class based on region, aspect, and elevation. The first factor is region. Historical data shows most hurricanes approach Puerto Rico from a northeast to southeast direction, meaning the hurricane will hit the east side of the island first. When Hurricane Hugo hit Puerto Rico in 1989, it significantly weakened as it passed over the Luquillo Mountains. Regional reconstructions of wind conditions showed an east-to-west gradient of maximum wind speed across eastern LEF caused by the storm track and the weakening of the storm after landfall. Damage at El Verde (on the west side of the mountain) was scattered and largely confined to defoliation and branch break, while Bisley (on the east side of the mountain) sustained catastrophic damage (including massive uprooting or breakage of a majority of stems) (Boose et al., 1994).

A damage gradient of Hurricane Hugo is illustrated in Table 4-3, with Class 5 being the worst damage and class 1 representing no damage. This table shows that the most severe damage occurred in the east section of the island.

Table 4-3 LEF Gradient Damage from Hurricane Hugo

Damage Risk Class	Region
5	Northeast section
4	Eastern half
3	Damage increased in western 2/3 of region
2	Damage increased in western 2/3 of region
1	North-east-to-southwest line across middle & western region

The second factor affecting hurricane damage risk is aspect. Most of Hurricane Hugo's damage occurred on north- to northwest- facing slopes, while south-facing slopes showed little damage (Boose et al., 1994).

The third hurricane damage factor is elevation. Class 5 (completely damaged) areas by Hurricane Hugo were mostly concentrated between 100 and 400 meters elevation and were confined to the Tabonuco forest area. Class 4 (damage) was primarily located in the Tabonuco forest below 600 meters. The Dwarf forest (the highest elevation forest area) is more resilient to wind damage than lower elevation forests, and had the least amount of damage (Boose et al., 1994).

The three factors listed above (region, aspect, and elevation) were used to create damage risk classes in a GIS file. FACET will use the risk class to either damage, blowdown, or leave alone trees in the plot area.

Hurricanes can have other effects, such as on soil. Soils in the LEF appear to be relatively resilient when exposed to severe aboveground disturbances. Mobile nutrients such as K and NO_3-N may decrease significantly initially, but most exchangeable soil nutrient pools were either the same as or greater than pre-disturbance levels after one to 6 years (Silver et al., 1996). Incorporating nutrient soil changes due to hurricanes in FACET is not an objective of this thesis.

SPECIES SUSCEPTIBILITY

A species susceptibility factor has been added which is based on a scale of 1 to 5 where 1 is most susceptible (very intolerant), 5 is least susceptible (very tolerant). This value is assigned to the variable S_i , which represents the likelihood of tree blowdown of species_i with susceptibility S_i.

Palms are resistant to hurricanes because they have relatively low leaf areas relative to trunk diameters and no limbs to break. Their leaves tend to trail in the wind rather than resisting it rigidly, so they are highly resistant to storm damage (Francis and Gillespie, 1993). Thus, palms are assigned a “5” for hurricane tolerance (low susceptibility).

Another consideration for species susceptibility is tree size. In general, larger trees are more susceptible than small trees. However, this can be mitigated by other factors, such as when tabonuco trees form root grafts with neighboring tabonuco trees, adding resistance and lessening total damage. Based on the aforementioned logic, hurricane susceptibility was assigned to each species, as listed in Table 4-4.

Table 4-4 Species Hurricane Susceptibility (1 very susceptible, 5 least susceptible)

Scientific Name	Hurricane Susceptibility
Miconia prasina	3
Casearia arborea	3
Inga laurina	2
Tabebuia heterophylla	3
Buchenavia capitata	2
Guarea guidonia	2
Manilkara bidendata	2
Dacryodes excelsa	4
Didymopanax morototoni	3
Cordia borinquensis	3
Daphnopsis philippiana	3
Ocotea leucoxylon	2
Cyrilla racemiflora	3
Micropholis garcinaefolia	3
Sloanea betreriana	2
Miconia tetranda	3
Calycogonium squamulosum	3
Tabebuia rigida	3
Prestoea montana	5
Cecropia schroeberiana	3
Psychotria berteriana	3

Implementation

The hurricane logic described above was incorporated into FACET. A hurricane frequency variable was added to the site file and thus can be varied by the user. In the FACET program, a “Hurricane” subroutine was created that is run from the main program before “Weather” and all other subroutines. The “Hurricane” subroutine randomly determines if it is a hurricane year. If it is, a hurricane category is randomly generated, as well as intensity associated with the various categories.

Hurricane risk class determined by location is input together with elevation, slope, aspect and soil type and thus becomes one more environmental factor to characterize terrain. For landscape characterization this hurricane damage risk class is assigned based on the specific elevation, region, and aspect as shown in Table 4-5. In this table, elevation is broken into ranges. The region code was calculated by classifying the LEF into three separate, equal regions: western, central and eastern. Aspect is defined as north, northeast, east, southeast, south, southwest, west, and northwest.

Table 4-5 Assigned Risk Classes

Elevation (meters)	Region*	Aspect	Risk
100 - 299, 400 - 1099	C	NW,N,NE	3
100 - 299, 400 - 1099	C	S,SW,W,E,SE	2
300 – 399	C	NW,N	3
300 – 399	C	S,SW,W,NE,E,SE	2
100 – 199	E	S,SW,E	3
100 – 199	E	SE	2
100 - 299, 700 - 799	E	NW,N	5
100 - 299, 700 - 799	E	W,NE	4
200 - 299, 700 - 799	E	S,SW,E,SE	3
300 – 399	E	NW,N	4
300 – 399	E	S,SW,E,SE	2
300 – 399	E	W,NE	3
400 – 599	E	NW	4
400 – 599	E	S,SW,NE,E,SE	2
400 – 599	E	W,N	3
600 – 699	E	E,SE	2
600 – 699	E	S,SW,NE	3
600 – 699	E	W,NW,N	4
0 - 599, 800-899	W	E	3
0 - 599, 800-899	W	S, SE	1
0 - 599, 800-899	W	SW,W,NW,N,NE	2
600 - 799, 900 - 999	W	S,SW,N,NE	2
600 - 799, 900 - 999	W	SE	1
600 - 799, 900 - 999	W	W,NW,E	3

*W = Western
*C = Central
*E = Eastern

The percentage wind-thrown trees that correspond to the classes shown in Table 4-5 are given in Table 4-6 (Boose, 1994).

Table 4-6 Damage Risk Classes

Class #	Risk Level	% Wind-Thrown Trees	% Selected
1	Undamaged	0	0
2	Slight damage	1 – 9	5
3	Moderate damage	10 – 39	25
4	Very damaged	40 – 74	57
5	Destroyed	75 – 100	87

For each risk class, the percentage windthrown as assigned in Table 4-6 is stored as variable *L*. This variable represents severity of damage as a function of location, which will be used later to calculate percentage blowdown.

Tree blowdown will be determined in the same subroutine that calculates stress and age-related death. The hurricane blowdowns are based on a combination of L, I, S_i where:

$M(S_i,L,I)$ = % tree blowdown due to hurricane intensity I at risk class L of species with susceptibility S_i

L= percent of damage as a function of location risk according to Table 4-6

I=intensity of hurricane, given as a function of hurricane category

Blowdowns were ranked according to these three factors, to increase proportionally with percentage damage by location risk (L) and intensity (I), and corrected by a fraction that decreases with susceptibility according to Table 4-7 from 1 to 0.6. Figure 4-1 illustrates the different tree blowdown percentages based on location, for each species susceptibility level, at a constant risk class of 80%. Figure 4-2, on the other hand, shows the varying tree blowdown percentages as a function of intensity for each species susceptibility at a constant severity of damage as location 3.

Table 4-7 Reduction Factor by Species Susceptibility to Hurricanes

Susceptibility	Reduction Factor
1	1.0
2	0.9
3	0.8
4	0.7
5	0.6

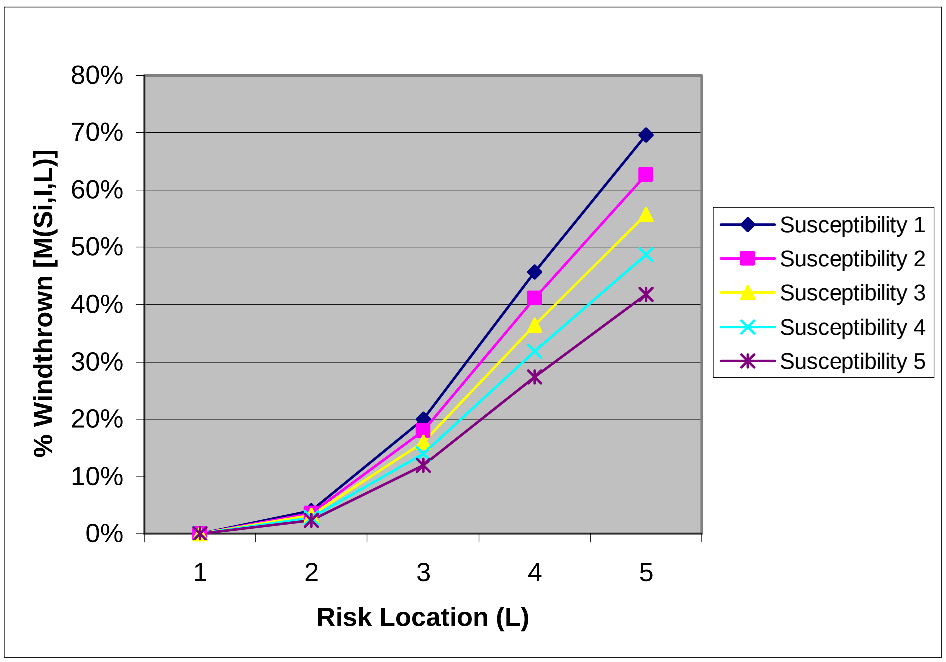

Figure 4-1 Tree % Blowdown as a Function of Risk Location for Fixed Intensity = 80%

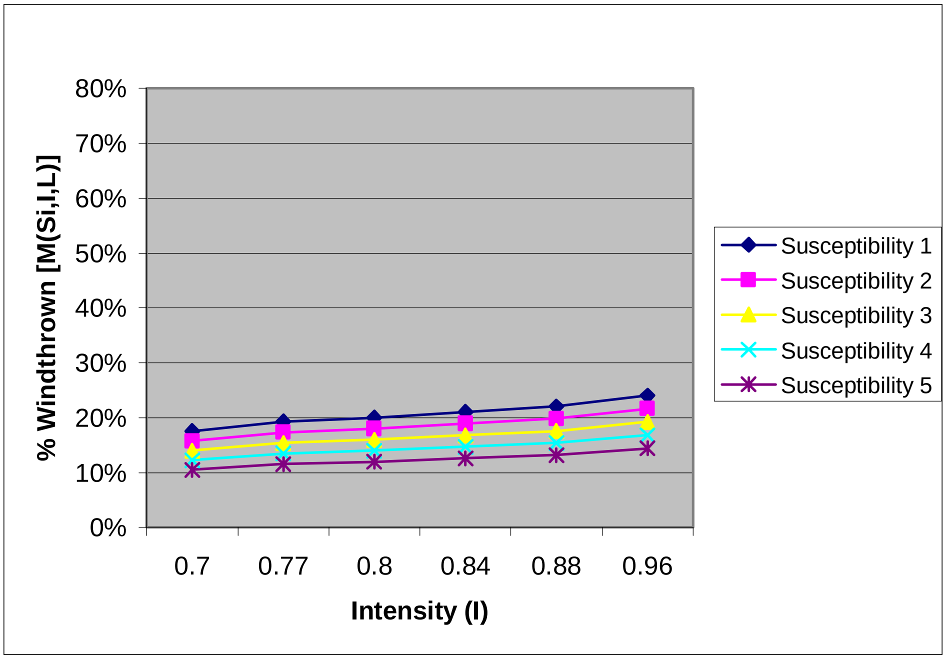

Figure 4-2 Tree % Blowdown as a Function of Intensity (I) for Fixed Location Risk Class = 3

An example of high damage due to a hurricane follows. First, a randomly generated Category 5 hurricane would have an intensity factor of 0.8. If the hurricane had high wind gusts and high precipitation, the multiplier would be 1.2. The resulting intensity value (I) is 0.96. If the geographic location was a Class 5 damage risk class, the percent windthrown is 88% according to Table 4-6. If the species had a high susceptibility (low tolerance) to hurricanes (S_i =1) the reduction factor would be set to 1.0 according to Table 4-7. The resulting tree blowdown percentage is $0.88 \times 0.96 \times 1.0 = 0.85$. Therefore, 85% of the trees in this high-damage scenario would be blown down.

On the opposite end of the spectrum, low damage caused by a hurricane is illustrated in the following example. First, a randomly generated Category 1 hurricane would have an intensity factor of 0.7. If the hurricane had low wind gusts and low precipitation, the multiplier would be 1.0. The resulting intensity value (I) would thus be 0.7. If the geographic location was a Class 2 damage risk class, the percent windthrown would be between 5% according to Table 4-6. If the species had a low susceptibility (high tolerance) to hurricanes ($S_i = 5$) the reduction factor would be 0.6 according to Table 4-7. The resulting tree blowdown percentage is: $0.7 \times 0.05 \times 0.6 = 0.02$. Therefore, 2% of the trees in this low-damage scenario would be blown down.

Include Response to Soil Water Logging

FACET includes drought tolerance or species response to lack of soil water. In the higher elevations of the LEF this type of situation is somewhat rare. Species often respond to the opposite situation: continuous soil saturation due to increased rainfall. Some species are less tolerant than others to excess soil moisture or soil water logging. Each LEF species was ranked based on soil water logging tolerance, and an excess soil water-factor was programmed in the soil water dynamics of FACET.

This factor is based on the same logic of the drought factor but using the accumulated number of wet days. These are defined as those days when soil water is greater than field capacity. The original FACET factor number of dry days is assigned a negative value, and the new wet days factor is assigned a positive value. Then a parabola is calculated based on a species preference for wet- and dry-days. In Figure 4-3, the tabonuco species growth rate multiplier based on soil moisture of between –0.5 (dry-days tolerance) and 0.88 (wet-days tolerance) is shown.

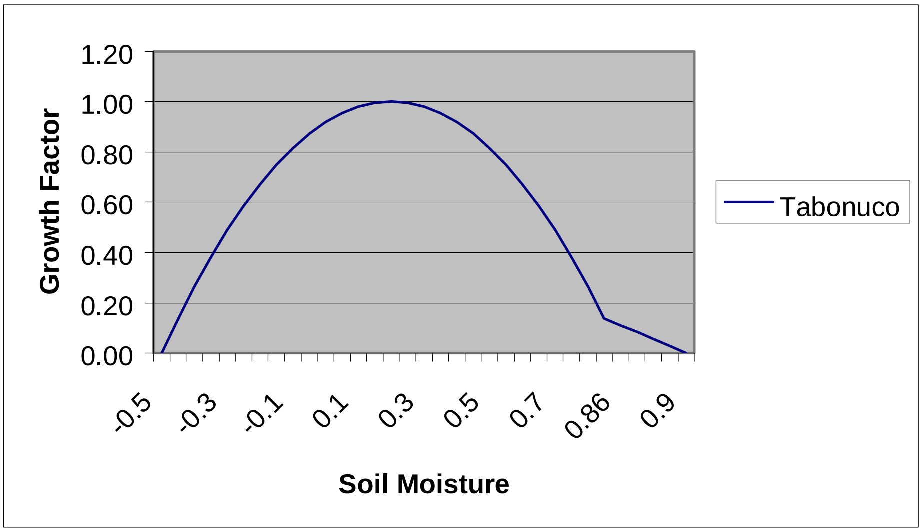

Figure 4-3 Tabonuco Soil Moisture Response

Calculated dry- and wet-day parabolas for Tabonuco, Colorado, and Dwarf forests for the known elevation ranges are displayed in Figure 4-5. Soil moisture increases with elevation because of the increased precipitation. The increase in soil moisture with elevation is shown in Figure 4-4.

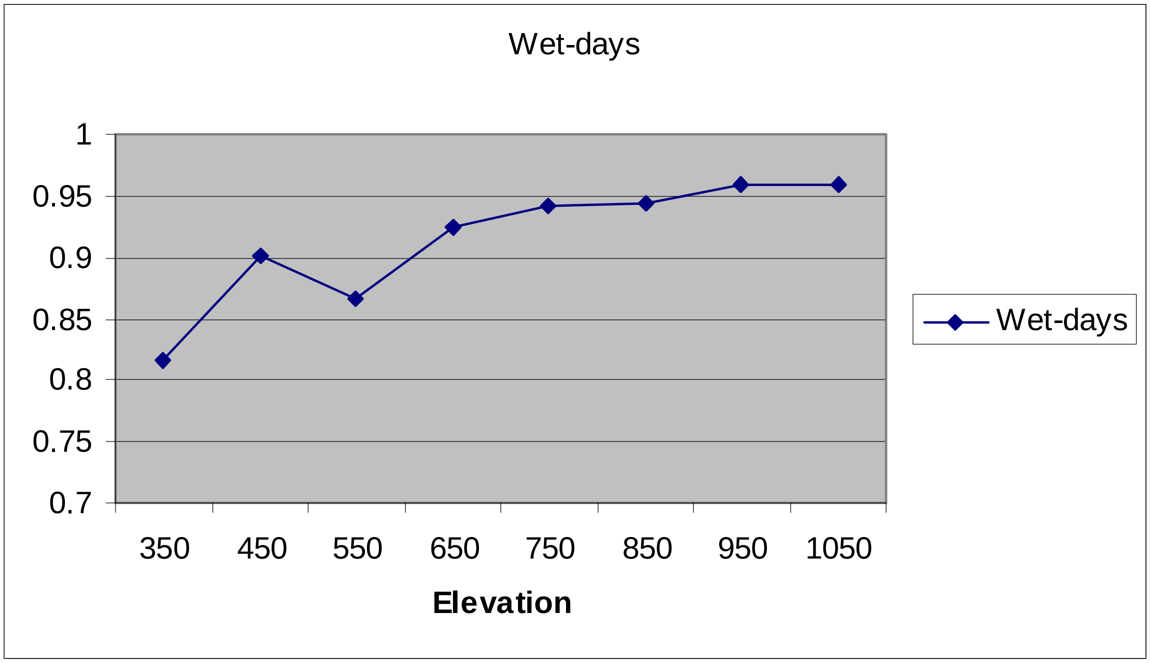

Figure 4-4 Soil Moisture (Wet-Days) as a Function of Elevation

However, modeled soil moisture was too highly variable for these more narrow soil moisture responses. Too often, moisture values fall outside of the parabola, causing the growth factor of soil moisture to be zero, and putting trees under stress. Trees do not grow well under such conditions.

The tolerances to dry-days were lowered and the tolerances to wet-days were increased. Thus, the ranges of non-zero values for the parabolas were widened, and trees were able to grow. Of course, wet-days no longer act to select species occurrence as a function of elevation. These new values are shown in Table 4-8. Reducing the dry-day and wet-day range according to elevation needs to be resolved with further research.

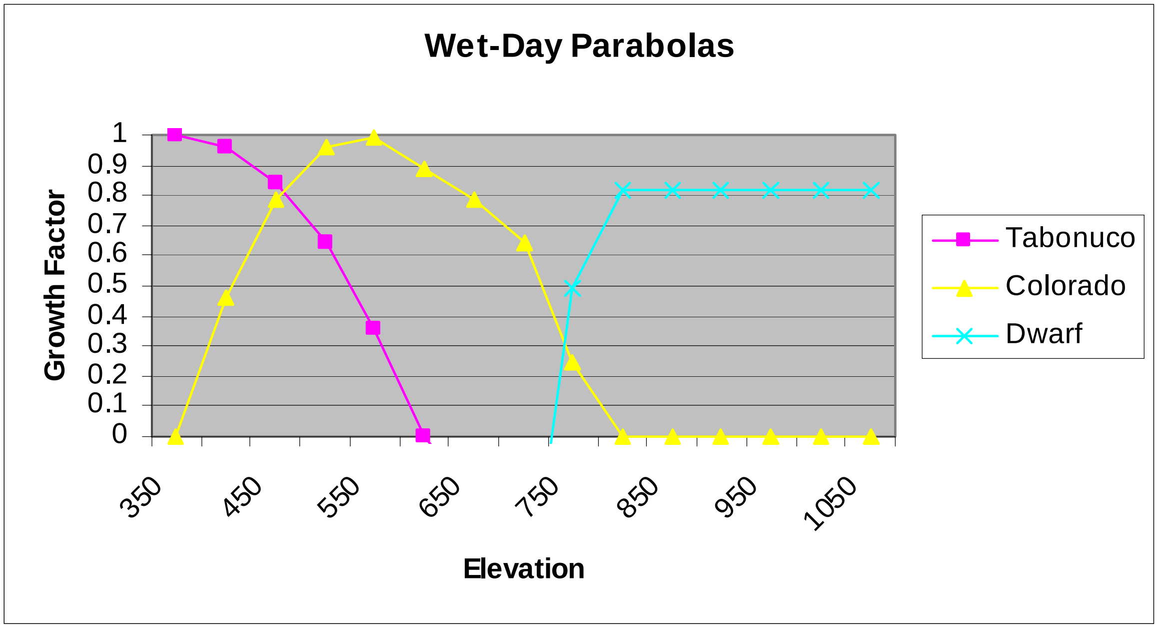

Figure 4-5 Wet-Day Parabolas for Major Forest Types

Table 4-8 Species Response to Soil Moisture

Scientific Name	Drought Tolerance	Wet Tolerance
Miconia prasina	0.25	1.25
Casearia arborea	0.25	1.25
Inga laurina	0.25	1.25
Tabebuia heterophylla	0.25	1.25
Buchenavia capitata	0.25	1.25
Guarea guidonia	0.25	1.25
Manilkara bidendata	0.25	1.25
Dacryodes excelsa	0.25	1.25
Didymopanax morototoni	0.25	1.25
Cordia borinquensis	0.25	1.25
Daphnopsis philippiana	0.25	1.25
Ocotea leucoxylon	0.5	1.5
Cyrilla racemiflora	0.5	1.5
Micropholis garcinaefolia	0.5	1.5
Sloanea betreriana	0.5	1.5
Miconia tetranda	0.5	1.5
Calycogonium squamulosum	0.3	1.3
Tabebuia rigida	0.5	1.5
Prestoea Montana	0.4	1.5
Cecropia schroeberiana	0.25	1.25
Psychotria berteriana	0.25	1.25

Landslides

Landslides affect less than 3% of the landscape per century. In the LEF, about 80% of landslides are less than 800 m^2. Much of the total landslide area is from a few large landslides (three landslides greater than 25,000 m^2 accounted for 49% of the area in the LEF) (Zimmerman et al., 1996).

Landslides usually occur in high rainfall and on the south side of forest and between 600 and 800 meters. It takes around 50 to 500 years to recover from a landslide

(Zimmerman et al., 1996). Landslide occurrence is controlled by five factors: slope, substrate composition and stability, precipitation, and land use.

The first factor is slope. Steep, concave slopes are more prone to sliding than shallow, convex ones. Research shows that recent landslides in the LEF had slopes ranging from 14 – 61 degrees.

The second factor is substrate composition and stability. In the LEF, landslides are more frequent on the more easily eroded quartz-diorite in the southern part of the forest than on the volcaniclastic rock located in the northern section of the forest.

Precipitation is the next controlling factor. The likelihood of a storm resulting in landslide depends on its intensity and duration. Conditions that can initiate landslides include: (1) storms greater than 100 – 200 mm, (2) a storm intensity greater than 13.8 mm/hour for several hours, or (3) rain totals of 2 –3 mm per hour if precipitation lasts for more than 100 hours. An average of 1.2 storms in the LEF each year produce landslides (Walker et al., 1996).

Land use is the final controlling factor. From 1964 – 1989, 53% of the total landslides were found to be road-related. Landslides are larger when they are associated with roads, and they are 2.4 times more frequent within 100 meters of road. Also, landslides are likely to reoccur at the same site (either within the original landslide or from the de-stabilized slope above it), unless the landslide has eroded back to the ridge top. One example of interest is one large landslide area in the LEF that has eroded frequently since its inception in 1979. The distance to the top of ridge is decreasing around 50 cm/year (Walker et al., 1996).

To predict where landslides may occur, the following indicators may be used: slope, substrate type, vegetative cover, road location, and previous landslide occurrence. Rainfall may also be estimated, and this amount used as a predictor.

Landslides can be divided into discrete zones in which degree of soil and vegetation removal, deposition, and stability may vary. Nearly complete removal of soil and vegetation, persistent erosion, and comparatively slow colonization by vegetation is found in the upper zone. Conversely, the lower zone does not erode for several years. This lower zone may be absent if the landslide area ends in a road or river where the eroded soils are removed. A middle zone may be present, which is usually a narrow transport chute connecting the upper and lower zones (Walker et al., 1996).

In the LEF, basal area and plant biomass can reach levels approximating values in adjacent mature forests within 55 years. High-elevation forest recovers slowly from disturbance. Stable, low-nutrient soils (not eroded for several years) found on the upper zone of LEF landslides are typically colonized by climbing ferns. Stable, high-nutrient soils located in the lower landslide zone favor rapid colonization and growth of pioneer tree species. At the higher elevations (>600 m), *Cyrilla racemiflora* is a colonizer of stable soils (Walker et al., 1996).

There is no predictable pattern of plant species recovery during landslide succession. Landslides increase forest-wide plant diversity because the area is predominantly colonized by pioneer species not present or abundant in nearby forest (Walker et al., 1996). The disturbance of landslides will not be added to FACET at this time, but may be added with further research at a later date.

Conclusions

One of the ways FACET was extended for the LEF was the addition of hurricanes. The user inputs minimum and maximum time for hurricane recurrence, then FACET randomly generates hurricane occurrence from a uniform distribution based on these inputs. In the future, with better statistics on hurricane frequency, this uniform distribution will be replaced with a more appropriate calculation.

FACET randomly generates a hurricane intensity factor based on a scale of 1 – 5 with equal probabilities. Future work will include different probabilities for each value of intensity. Tree damage is determined in part by this intensity factor. Later work will add a sliding scale for recurrence time as higher-intensity storms do not occur as often as low-intensity. In addition, a multiplier effect was added based on damage due to wind gusts and precipitation. Also, a damage risk class was added to account for region (west side of the LEF experiences less damage than east), aspect (a recent storm showed less damage on north and west aspects), and elevation (the higher the elevation, the lower the damage). Finally, a species susceptibility factor was assigned to account for individual species' ability to resist hurricanes. Hurricane scenarios were tested and as expected, higher tree damage occurred in more intense storms in a higher risk class location for more susceptible species, and vice versa.

FACET formerly only included a species' response to dry conditions. To accommodate the wet conditions of the LEF, parabolas were calculated based on individual species preferences for wet- and dry-days. However, soil moisture was too variable in FACET, so the parabolas were widened. Further work will address this model’s sensitivity to soil moisture. Also, landslides may be added to FACET in the future.

CHAPTER 5 SEMAPAR: TERRAIN AND COVER TYPES

Terrain: GIS files

Parameterization of MOSAIC over the entire landscape requires defining those relief and environmental variables that make vegetation response vary across the landscape. MOSAIC is a semi-Markovian transition model (Dr. Miguel Acevedo, University of North Texas, Department of Geography, Denton, TX, 76203). Combinations of values for these environmental and terrain conditions make up a number terrain types relevant for the study area. For LEF, terrain types are defined according to combinations of five relief and environmental factors: elevation, slope, aspect, soil type and hurricane risk class. Each one of these factors is determined across the landscape in the form of a GIS file. Then, these five files are combined to determine the terrain type of each region or cell in the landscape.

ELEVATION, SLOPE, AND ASPECT

Three of the terrain types for the LEF are elevation (Figure 5-1), slope (Figure 5-2), and aspect (Figure 5-3). The slope and aspect files were created from the elevation file using the ArcGIS Spatial Analyst Surface Analysis tool.

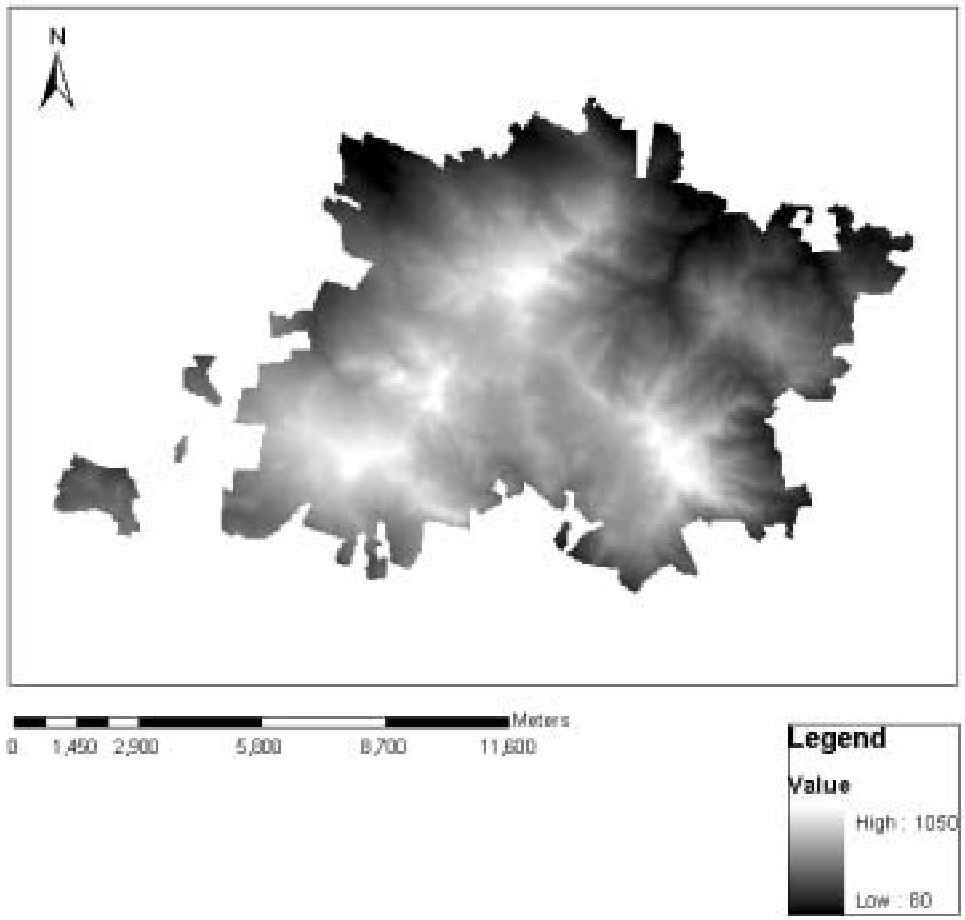

Figure 5-1 LEF Elevation GIS File (meters)

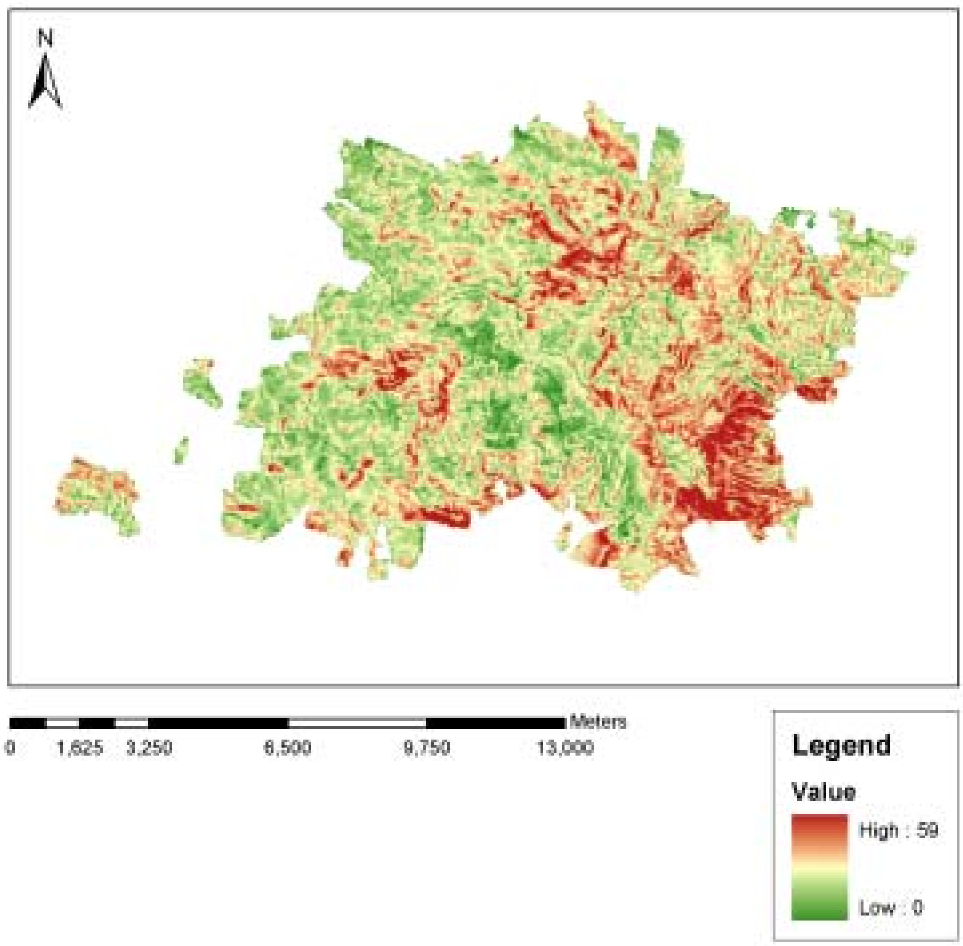

Figure 5-2 LEF Slope GIS File (%)

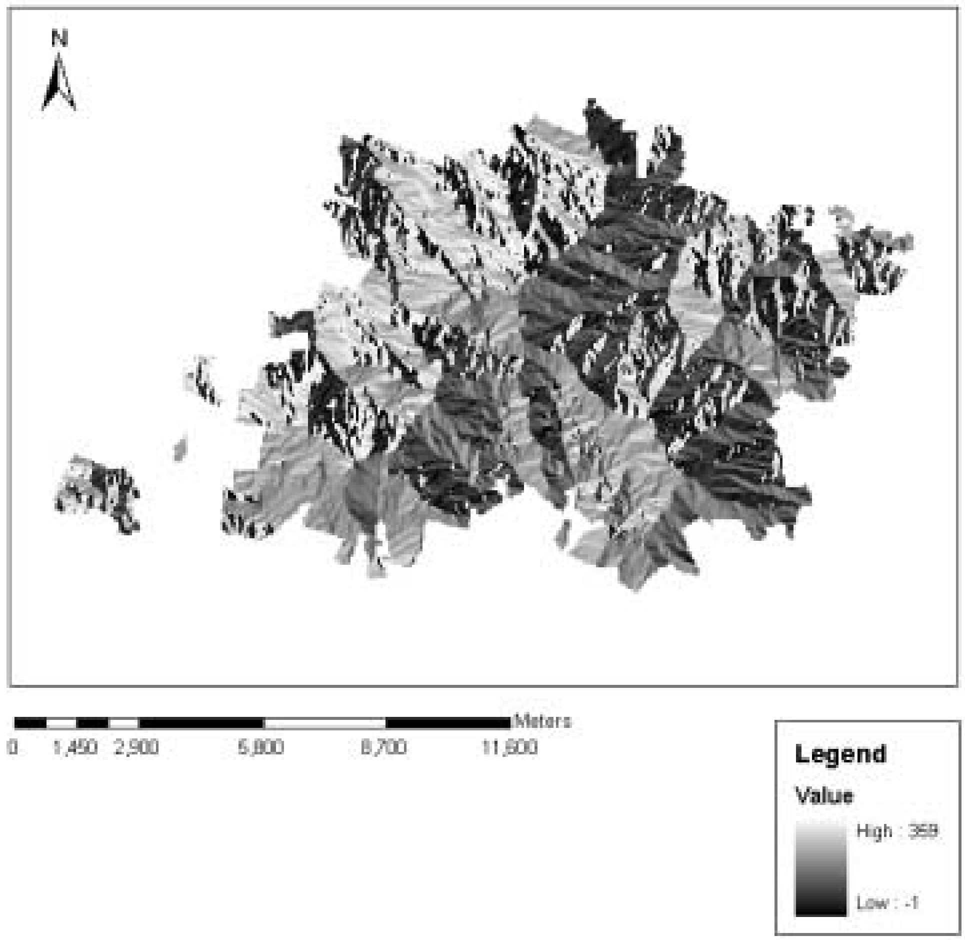

Figure 5-3 LEF Aspect GIS File (degrees)

SOILS

The soil GIS file available from the LEF Website (http://sunites.upr.clu.edu/sunceer/, 2001) has soil mapping units instead of individual soil series. Soil mapping units contain one to three individual soil series. These mapping units can be broken down by looking at the slope. For instance, in the Zarzal-Cristal mapping unit, the soil is Zarzal if it has a steeper slope, but it is Cristal if it has a less steeper slope.

The LEF soil file lists all of the soil mapping units in the soil survey, plus some private areas (see Figure 5-4 with soil codes corresponding to Table 5-1). Thirteen of the 21 soil mapping units are a combination of two or more soil series that need to be broken down into the individual soil series in order to properly reflect soil factors in FACET (see Table 5-1). FACET is a gap model derived as a relief-sensitive version of the spatially-explicit ZELIG gap model (Urban et al., 1991, Urban and Shugart, 1992) (Dean L. Urban, FACET and ZELIG version 2, Department of Forest Sciences, Colorado State University, Fort Collins, CO 80523).

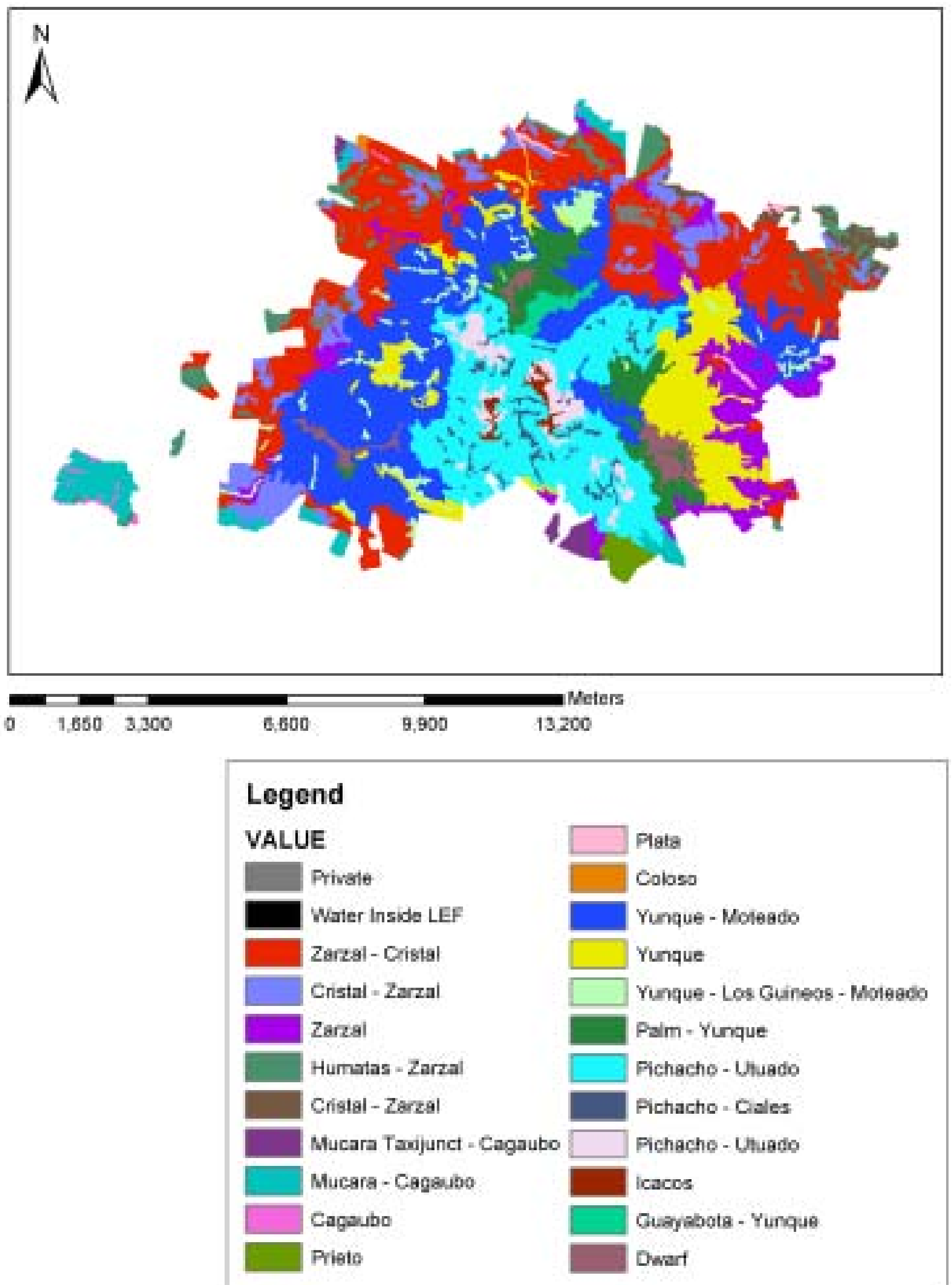

Figure 5-4 LEF Soil Mapping Units Coverage

Table 5-1 Soil Mapping Unit Coverage Codes

Code	Description
0	Private
97	Water outside LEF
98	Water inside LEF
112	Zarzal – Cristal
113	Cristal – Zarzal
114	Zarzal
115	Humatas - Zarzal
117	Cristal – Zarzal
121	Mucara Taxijunct – Cagaubo
131	Mucara – Cagaubo
132	Cagaubo
135	Prieto
141	Plata
142	Coloso
212	Yunque – Moteado
213	Yunque
214	Yunque – Los Guineos – Moteado
215	Palm – Yunque
221	Picacho – Utuado
223	Picacho – Ciales
224	Picacho – Utuado
225	Icacos
231	Guayabota – Yunque
311	Dwarf

In order to break the soil mapping units into individual soil series, the soil coverage needs to have slope information added to it. The LEF slope file and the soil file were overlain. The slope and soil files were combined and an additional field for individual soil series was added. Then, a program was written to break out the soil mapping units into individual soil types. The code logic follows:

```
If (soil mapping unit = 112) AND (slope < 30) then Soil = Cristal
If (soil mapping unit = 112) AND (slope >= 30) then Soil = Zarzal
If (soil mapping unit = 113) AND (slope <= 28) then Soil = Cristal
If (soil mapping unit = 113) AND (slope > 28) then Soil = Zarzal
If (soil mapping unit = 114) then Soil = Zarzal
If (soil mapping unit = 115) AND (slope < 20) then Soil = Humatas
If (soil mapping unit = 115) AND (slope >= 20) then Soil = Zarzal
If (soil mapping unit = 117) AND (slope < 18) then Soil = Cristal
If (soil mapping unit = 117) AND (slope >= 18) then Soil = Zarzal
If (soil mapping unit = 121) AND (slope <= 40) then Soil = Cagaubo
If (soil mapping unit = 121) AND (slope > 40) then Soil = Mucara
If (soil mapping unit = 131) AND (slope <= 55) then Soil = Mucara
If (soil mapping unit = 131) AND (slope > 55) then Soil = Cagaubo
If (soil mapping unit = 132) then Soil = Cagaubo
If (soil mapping unit = 135) then Soil = Prieto
If (soil mapping unit = 141) then Soil = Plata
If (soil mapping unit = 142) then Soil = Coloso
if (soil mapping unit = 212) AND (slope <= 40) then Soil = Moteado
If (soil mapping unit = 212) AND (slope > 40) then Soil = Yunque
If (soil mapping unit = 213) then Soil = Yunque
If (soil mapping unit = 214) AND (slope <= 14) then Soil = Los Guineos
If (soil mapping unit = 214) AND (slope = 15 - 17) then Soil = Moteado
If (soil mapping unit = 214) AND (slope >= 18) then Soil = Yunque
If (soil mapping unit = 215) AND (slope <= 60) then Soil = Yunque
If (soil mapping unit = 215) AND (slope > 60) then Soil = Palm
If (soil mapping unit = 221) AND (slope <= 60) then Soil = Picacho
If (soil mapping unit = 221) AND (slope > 60) then Soil = Utuado
If (soil mapping unit = 223) AND (slope <= 18) then Soil = Ciales
If (soil mapping unit = 223) AND (slope > 18) then Soil = Picacho
If (soil mapping unit = 224) AND (slope <= 30) then Soil = Utuado
If (soil mapping unit = 224) AND (slope > 30) then Soil = Picacho
If (soil mapping unit = 225) then Soil = Icacos
If (soil mapping unit = 231) AND (slope <= 55) then Soil = Guayabota
If (soil mapping unit = 231) AND (slope > 55) then Soil = Yunque
If (soil mapping unit = 311) then Soil = Dwarf
```

After executing this program, the results were analyzed. Some of the mapping units were not properly broken out. For instance, soil mapping unit 212 is approximately 45% Yunque and 25% Moteado. After running the code found above, there were mostly Moteado individual soil types.

To improve the proper breakout of soil mapping units into individual soil series, the slope data was analyzed to find better slope cutoff points. For instance, soil mapping unit 212 was broken out based on all slopes greater than 40 percent. However, Moteado represented 75 percent of the soil map, when it should only account for 25 percent. After analyzing the data, 22 percent slope seemed like a better cutoff point, resulting in 28 percent of the soil map being Moteado. There is no way to obtain an exact cutoff of 25 percent because there are many soil mapping units for one corresponding slope integer value.

After determining better slope cut-off points for breaking out the soil mapping units, the code logic was changed. The code changes:

```
If (soil mapping unit = 212) AND (slope <= 23) then Soil = Moteado
If (soil mapping unit = 212) AND (slope > 23) then Soil = Yunque
If (soil mapping unit = 215) AND (slope <= 40) then Soil = Yunque
If (soil mapping unit = 215) AND (slope > 40) then Soil = Palm
If (soil mapping unit = 224) AND (slope <= 11) then Soil = Utuado
If (soil mapping unit = 224) AND (slope > 11) then Soil = Picacho
If (soil mapping unit = 231) AND (slope <= 37) then Soil = Guayabota
If (soil mapping unit = 231) AND (slope > 37) then Soil = Yunque
```

The improved logic was run on the soil/slope coverage, and individual soil series coverage was created. The polygons were then dissolved based on the individual soil (see Figure 5-5). Now each plot contains only one individual soil series.

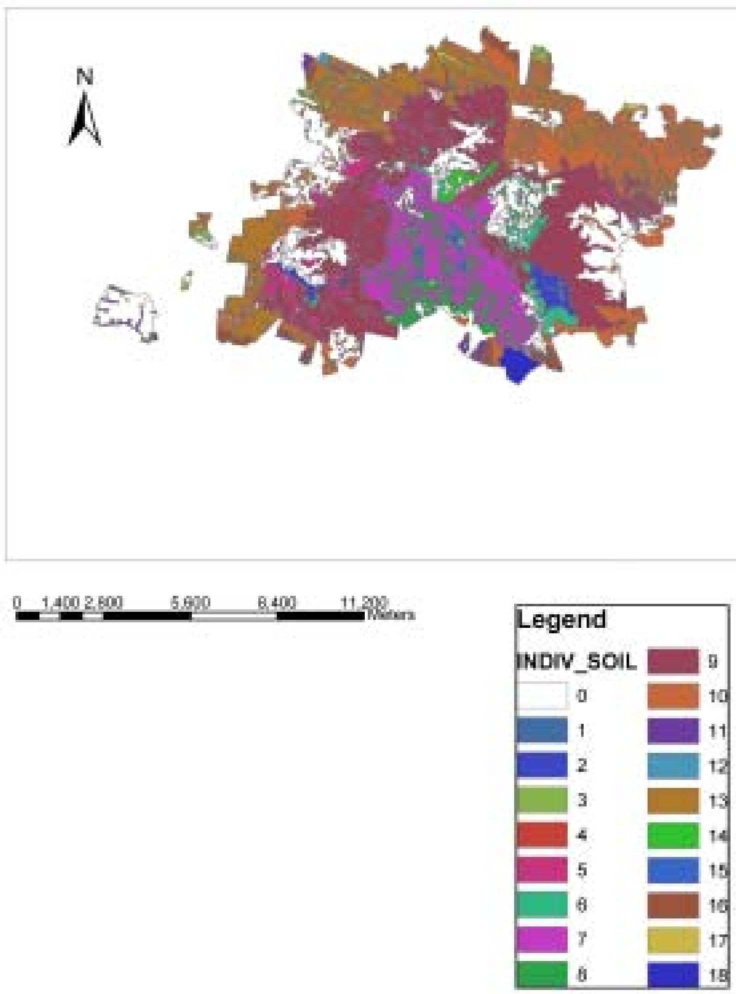

Figure 5-5 Individual Soil Series Coverage

However, 18 soil types combined with several elevation, slope, aspect and hurricane risk classes would result in a large amount of SEMAPAR runs as discussed later in this chapter. To reduce the number of SEMAPAR runs, the original soil mapping unit combinations from the survey were used for terrain combinations. See Table 5-2 for the original soil survey combinations and the new soil combinations. Soil types are reduced from the original 21 to seven. These seven soil types are found in Table 5-3.

Table 5-2 Soil Combinations from Soil Survey

Original Code	Description	New Soil Combination
0	Private	N/A
97	Water outside LEF	N/A
98	Water inside LEF	N/A
112	Zarzal – Cristal	Zarzal – Cristal – Humatas
113	Cristal – Zarzal	Zarzal – Cristal – Humatas
114	Zarzal	Zarzal – Cristal – Humatas
115	Humatas – Zarzal	Zarzal – Cristal – Humatas
117	Cristal – Zarzal	Zarzal – Cristal – Humatas
121	Mucara Taxijunct – Cagaubo	Mucara – Cagaubo
131	Mucara – Cagaubo	Mucara – Cagaubo
132	Cagaubo	Mucara – Cagaubo
135	Prieto	Prieto – Coloso
141	Plata	Icacos – Plata
142	Coloso	Prieto – Coloso
212	Yunque – Moteado	Yunque – Moteado – Los Guineos – Palm – Guayabota
213	Yunque	Yunque – Moteado – Los Guineos – Palm – Guayabota
214	Yunque – Los Guineos – Moteado	Yunque – Moteado – Los Guineos – Palm – Guayabota
215	Palm – Yunque	Yunque – Moteado – Los Guineos – Palm – Guayabota
221	Picacho – Utuado	Picacho – Utuado – Ciales
223	Picacho – Ciales	Picacho – Utuado – Ciales
224	Picacho – Utuado	Picacho – Utuado – Ciales
225	Icacos	Icacos – Plata
231	Guayabota – Yunque	Yunque – Moteado – Los Guineos – Palm – Guayabota
311	Dwarf	Dwarf

Table 5-3 Resulting Soil Combinations

#	New Soil Combination
1	Zarzal – Cristal – Humatas
2	Mucara – Cagaubo
3	Prieto – Coloso
4	Yunque – Moteado – Los Guineos – Palm – Guayabota
5	Picacho – Utuado – Ciales
6	Icacos – Plata
7	Dwarf

For the new soil combinations found in Table 5-3, the soil parameters were averaged assuming that they are evenly distributed. An example of the averaging of soil layer depth, field capacity and wilting point is found in Table 5-4 for the Prieto – Coloso soil combination.

Table 5-4 Prieto – Coloso Soil Combination

Prieto			Coloso			Average		
Layer Depth	Field Capacity	Wilting Point	Layer Depth	Field Capacity	Wilting Point	Layer Depth	Field Capacity	Wilting Point
10	4.4	3	10	3.8	2.4	10	4.10	2.70
10	4.5	3.1	10	3.9	2.5	10	4.20	2.80
10	4.6	3.1	10	3.8	2.4	10	4.20	2.75
10	4.3	2.8	10	4	2.5	10	4.15	2.65
10	4.3	2.8	10	4.1	2.6	10	4.20	2.70
10	3.8	2.2	10	4.1	2.6	10	3.95	2.40
10	3.8	2.2	10	4.1	2.6	10	3.95	2.40
10	3.8	2.2	10	4.1	2.6	10	3.95	2.40
10	3.8	2.2	10	4.1	2.6	10	3.95	2.40
10	3.8	2.2	10	4.1	2.6	10	3.95	2.40
10	3.6	2	10	3.7	2.2	10	3.65	2.10
10	3.6	2	10	3.7	2.2	10	3.65	2.10
5	1.9	1.05	5	1.85	1.1	5	1.88	1.08

However, since individual soil information has been determined, the number of soil types can be increased in the future.

HURRICANES

As discussed in Chapter 4, hurricane damage risk classes are based on elevation, aspect, and region. Figure 5-6 shows the hurricane risk class GIS file which corresponds to Table 4-5. To obtain this file, the elevation GIS file was first reclassified into 100-meter ranges and made into separate files. Then, region code was calculated by breaking the LEF into three separate, equal regions of western, central and eastern and also put into individual files. Aspect was classified into north, northeast, east, southeast, south, southwest, west, and northwest, again, put into separate files. Then, files were combined based on the logic found in Table 4-5 and made into hurricane risk class files. The final step was to add all the files together to create one hurricane risk file.

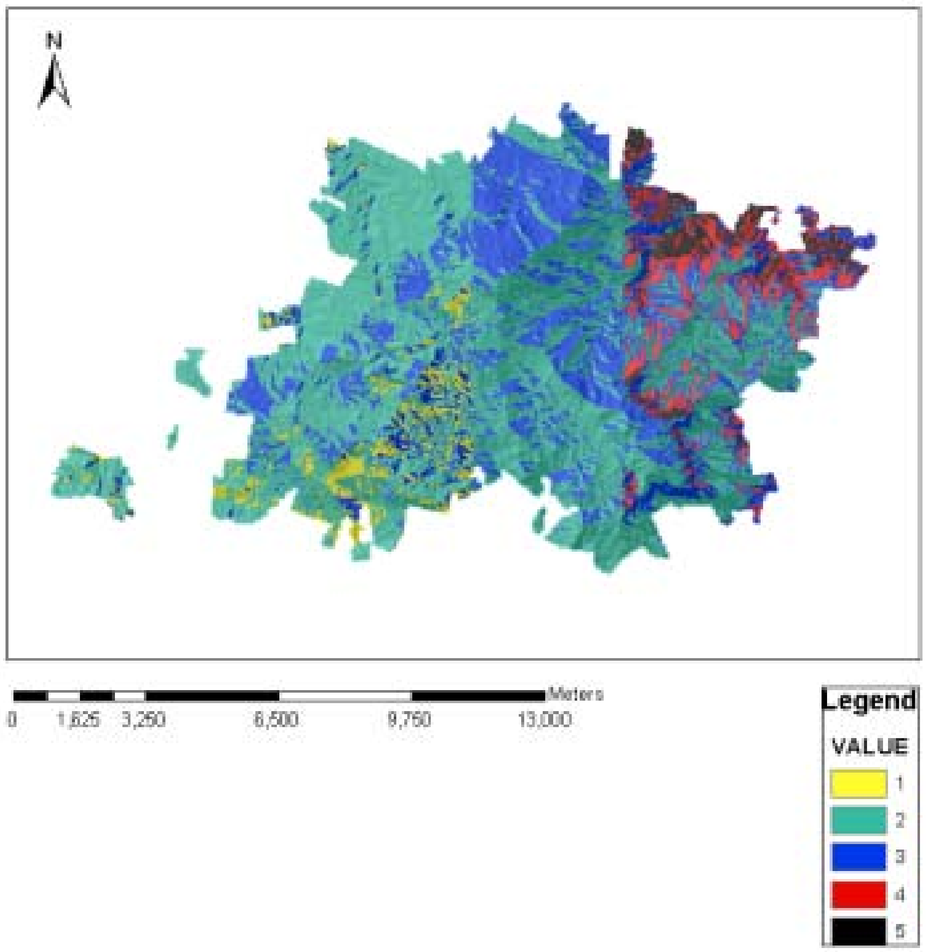

Figure 5-6 Hurricane Risk Class

Gradient Space Classes: Define Terrain Types

Terrain types for the LEF are given by combinations of the five terrain/environmental variables just determined: elevation, slope, aspect, soil type and hurricane risk class. SEMAPAR is a MOSAIC parameter estimation program that calculates MOSAIC parameter values from a FACET simulation run initialized from gap or bare ground. Code added to FACET generates files containing the cover type of each gap model plot through time. These files are input into SEMAPAR, which counts the number of transitions between each pair of states (to estimate transition probabilities), a fixed delay for each transition and the two parameter values of a gamma-distributed delay for each transition.

These calculations are conducted for a FACET run executed for a given terrain type or combination of the five environmental variables. Therefore, a large number of combinations lead to a computer-intensive process. The number of combinations depends on the number of categories selected for each one of the five environmental factors. One way of reducing the number of terrain types to a manageable amount is to reduce the number of categories for the factors except for those that are more sensitive. Small intervals for the categories are selected only where FACET is more sensitive. For this purpose, SEMAPAR is run along gradients of each environmental factor. To determine these gradients, each factor is sampled in small uniform steps across its range while keeping other factors constant (Acevedo et al., 2001b).

A reduction of categories of soil types to seven was already discussed in the previous chapter. Elevation is an important environmental gradient in LEF and it was decided to vary in relatively fine steps of 100 m, from 350 to 1050 m. For a first parameterization slope and aspect were kept at constant values (just one category for each). Therefore, the SEMAPAR runs will be based on the values for terrain factors given in Table 5-5.

Table 5-5 FACET Terrain Type Values

Terrain Type	Range of Possible Values	Values Selected	Number of Categories
Soil Series	18 types	7 (see Table 5-3)	7
Hurricane	5 risk classes	1,2,3,4,5	5
Elevation	300 – 1079 meters	350,450,550,650,750, 850,950,1050	8
Aspect	0 - 360 degrees	90 degrees (E)	1
Slope	0 – 60%	20%	1

To include every possible (full factorial) combination of the environmental terrain conditions found in Table 5-5 results in 280 terrain types (7 x 5 x 8 x 1 x 1). The number of terrain types can be increased in future work when required by more refined analysis.

Cover type

Classification of cover types for MOSAIC have included species dominance and age in the H.J. Andrews (Acevedo et al., 1995) and species shade tolerance and tree height as well as canopy height in Imataca (Delgado, 2000). For the LEF we combined dominance by species of the four forest types (Palm, Colorado, Tabonuco and Dwarf) with canopy height. An additional group of species was defined as "Adaptive" because they are present in all forest types. The five types: Adaptive, Tabonuco, Palm, Colorado, and Dwarf are coded from 1 to 5 as given in Table 5-6. The associated forest types for each species are shown in Table 5-7.

Canopy height (see Table 5-8) is combined with dominance by basal area of representative species for each one of these five types (see Table 5-9). The classification scheme was coded in function “ntype.f” and called from FACET’s “grid.f” routine.

Table 5-6 Representative Species

1	Adaptive
2	Tabonuco
3	Colorado
4	Palm
5	Dwarf

Table 5-7 Species and Respective Forest Types

Scientific Name	Forest Type
Cecropia schroeberiana	1
Psychotria berteriana	1
Didymopanax morototoni	1
Cordia borinquensis	1
Daphnopsis philippiana	1
Calycogonium squamulosum	1
Miconia prasina	2
Casearia arborea	2
Inga laurina	2
Tabebuia heterophylla	2
Buchenavia capitata	2
Guarea guidonia	2
Manilkara bidendata	2
Dacryodes excelsa	2
Ocotea leucoxylon	3
Cyrilla racemiflora	3
Micropholis garcinaefolia	3
Sloanea betreriana	3
Miconia tetranda	3
Prestoea montana	4
Tabebuia rigida	5

Table 5-8 Canopy Heights

Canopy heights (m)	
Low	$H < 10$
Med	$10 \leq H \leq 16$
High	$H > 16$

Table 5-9 State Based on Height and Basal Area Dominance

State	Canopy Height	BA Dominant Species
1	L	Gap
2	L	1
3	L	2
4	L	3
5	L	4
6	L	5
7	M	1
8	M	2
9	M	3
10	M	4
11	M	5
12	H	1
13	H	2
14	H	3
15	H	4
16	H	5

Currently, the canopy height associated with low, medium and high categories is the same for all forest types. However, each forest type has different canopy heights associated with successional and mature forests. Thus, a more accurate breakdown would have a different canopy height for each forest type. For instance, the Dwarf forest would have a high canopy height that is lower than the other forest types' high canopy height because these species do not grow as tall as the other species. This will not be addressed for the purposes of this thesis but should be included in future work.

Initial Condition

FACET is started from bare ground and run for hundreds of years to arrive at a state that should be comparable to what is currently found in the LEF. Or, an input file can be used with whatever starting state is desired and run for any number of years. This latter method may be preferable using the LEF's current state as input. This will properly reflect the results of any past disturbances, both by natural disaster and anthropogenic alteration. This is important as far as human effects because these can be clearly visible on species composition after 60 years of abandonment (Zimmerman et al., 1995). Also, age of abandoned pastures will be properly reflected if an input of the current LEF make-up is used. This age since abandonment is the best predictor of forest recovery in abandoned pastures in higher elevation LEF (Aide et al., 1996).

Conclusions

Terrain factors were identified that caused vegetation to respond: elevation, slope, aspect, soils, and hurricane risk class. These factors are calculated for the entire LEF using GIS files. Three of these files (elevation, slope, and aspect) were previously available. A GIS soils file was available and contained combined soil series called mapping units. These mapping units were broken down into individual soil series based on slope. However, they were later combined based on similar characteristics to reduce the number of FACET simulation runs and SEMAPAR calculations. But since the individual soil series file exists, this can be used in the future for individual soil information or different combinations. A hurricane risk class GIS file was created based on elevation, aspect, and region.

Terrain types for the LEF are combinations of the above mentioned GIS factors of elevation, slope, aspect, soil, and hurricane risk class. Each factor was divided into categories to make the number of FACET simulation runs and SEMAPAR calculations manageable. Two hundred and eighty terrain types were defined using eight elevation categories, seven soil types, and five hurricane risk classes. Slope and aspect were maintained constant at 20% and 90 degrees respectively.

Resulting cover type classification was based on the four forest types (Tabonuco, Colorado, Dwarf, and Palm) plus an additional Adaptive forest type. Sixteen MOSAIC states are defined by three canopy heights and forest type corresponding to the dominant species (by basal area). A future improvement is to assign a different canopy height to each forest type as the forest type species grow to different heights.

CHAPTER 6 FACET EVALUATION

FACET, which is a gap model derived as a relief-sensitive version of the spatially-explicit ZELIG gap model (Urban et al., 1991, Urban and Shugart, 1992) (Dean L. Urban, FACET and ZELIG version 2, Department of Forest Sciences, Colorado State University, Fort Collins, CO 80523), was evaluated using runs for selected terrain types selected from combinations of environmental factors elevation, slope, aspect, soil type and hurricane risk. Terrain types are discussed in chapter 5 for the purpose of parameterizing MOSAIC from FACET using SEMAPAR. MOSAIC is a semi-Markovian transition model (Dr. Miguel Acevedo, University of North Texas, Department of Geography, Denton, TX, 76203). For the purpose of evaluating FACET we will select fewer terrain types and emphasize gradients of elevations.

As explained in Chapter 1, FACET parameter values were adjusted to match published data and known species distribution in the LEF. Recent data collected for the Quebrada Sonadora along an elevational gradient from El Yunque Peak to the EVFS (the El Verde Field Station) were used as the main data set for FACET evaluation.

Elevation Gradient

Figure 6-1 shows FACET's prediction of basal area for representative species of each main forest type at varying elevations at the end of a 1000-year simulation run. This is for the base run at hurricane risk class one, representing no damage due to hurricanes. Slope is set to 20, aspect is set to 90, and soil type is set to one. Figure 6-2 and Figure

6-3 show the basal area for the same set of species and parameters with hurricane risk class set to two and three respectively. Figure 6-4 shows the basal area for these same species in a recent study along an elevational gradient of the LEF (Barone, personal communication).

For elevation ranges, the tabonuco (*Dacryodes excelsa*) species is present in a range from 350 to 650 meters in FACET output. In the recent study, the tabonuco shows a dip at around 500 meters and does not taper off until 750 meters. The palo colorado (*Cyrilla racemiflora*) species range from FACET is approximately 600 to 975 meters. In the recent study, the palo colorado's range is about 675 to 975 meters. The Dwarf species *Tabebuia rigida* has a range above 850 meters in FACET. The recent study did not encounter this species in the Dwarf forest. Instead, the study shows the *Tabebuia rigida* growing in the Colorado forest. In FACET, this species also occurs in the Colorado forest, but with different growth rates, maximum dbh, and height. However, the species is commonly found in the Dwarf forest (Weaver, 1983), but the distribution appears patchy.

For basal area, the Tabonuco is higher per FACET than the recent study, but is closest to the study values for hurricane risk class 3 (less than 20 m^2/ha vs. less than 10 m^2/ha). For the Colorado species, the values in hurricane risk class 3 are fairly close to the recent study values (approximately 20 m^2/ha vs. around 15 m^2/ha). For reasons mentioned above, the *Tabebuia rigida* is found in FACET but not in the recent study.

The recent study so far only shows the results of one transect. Once the other remaining transects are finished, a more complete picture could be shown. Then a more accurate comparison can be made between FACET and the actual LEF species composition. This is future work. Based on comparison to this partial study, FACET is sometimes computing basal areas that are too high. Future work will determine the cause for this and correct it.

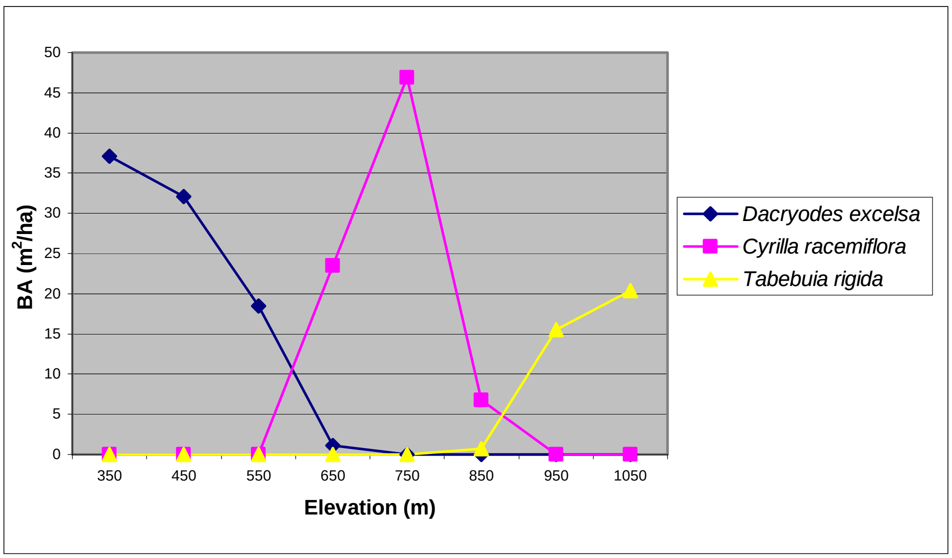

Figure 6-1 FACET Species Response to Elevation Hurricane Risk Class 1

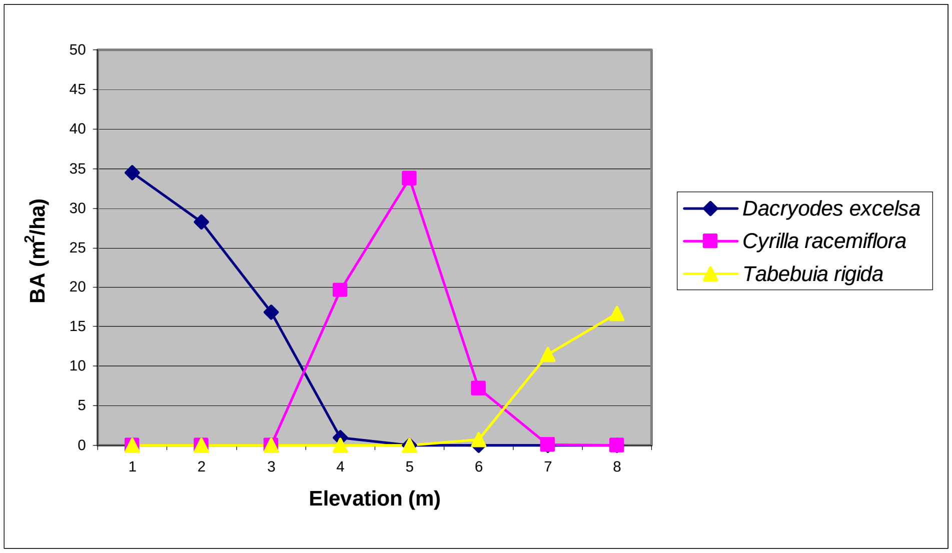

Figure 6-2 FACET Species Response to Elevation Hurricane Risk Class 2

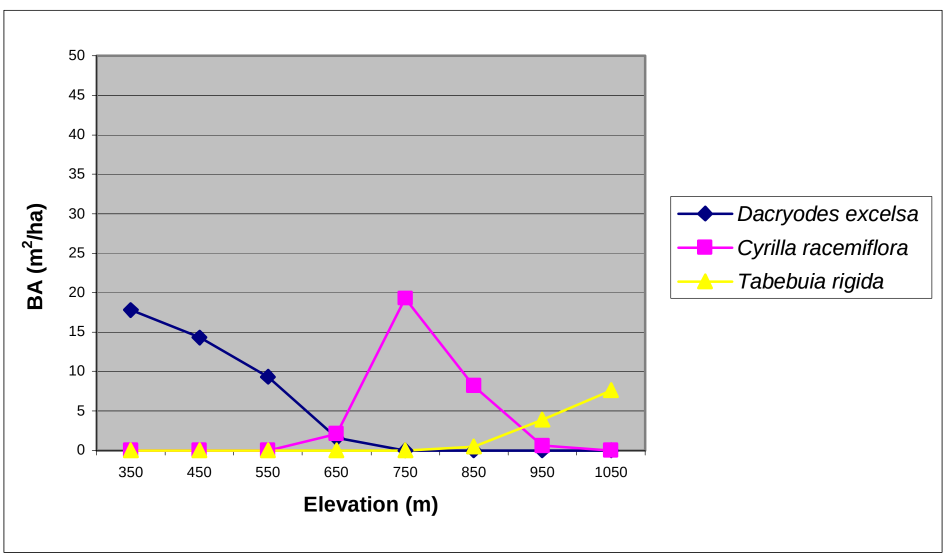

Figure 6-3 FACET Species Response to Elevation Hurricane Risk Class 3

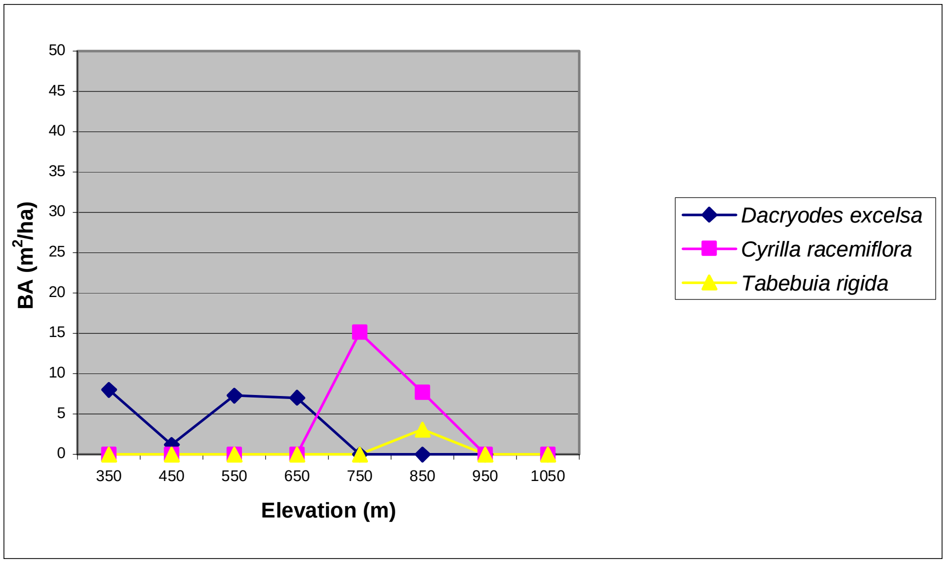

Figure 6-4 Recent Study Species Response to Elevation (Barone, personal communication)

Long-term Stand Composition

Comparisons in this section between FACET and the recent study are made for soil type 1, slope 20, and aspect 90. Figure 6-5 shows the comparison of stand composition between FACET at hurricane risk levels of 1, 2, and 3 and the recent study at 350 meters. Table 6-1 lists the species mnemonic for each species. As discussed earlier, the tabonuco's (DACEXC) basal area is much higher per FACET at each hurricane risk class than the study. The study also shows that *Guarea guidonia* (GUAGUI), *Sloanea betreriana* (SLOBER), and *Alchorneopsis floribunda* (ALCFLO) have higher basal areas than FACET. In addition, the palm shows lower basal area in the FACET results.

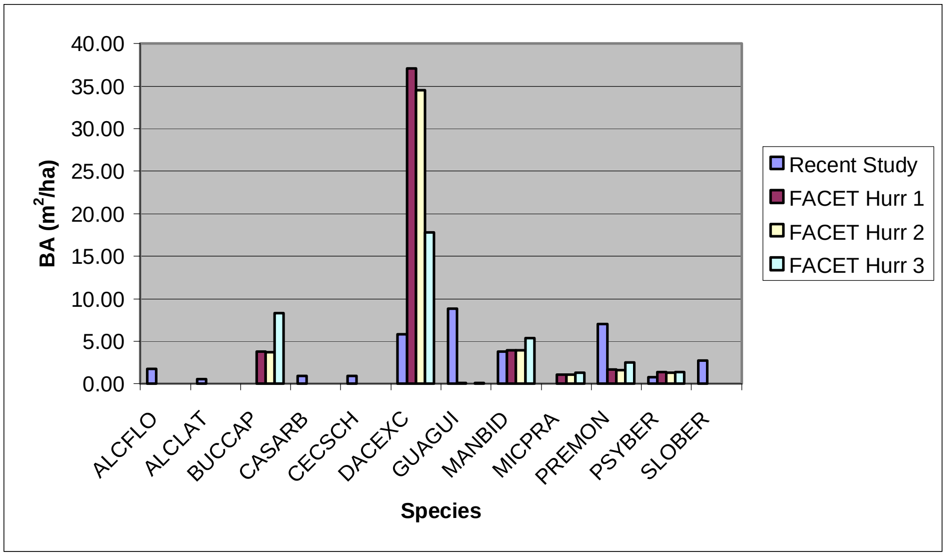

Figure 6-5 Basal Area Comparison Between FACET and Recent Study at 350 meters

Table 6-1 Species Mnemonics

Scientific Name	Mnemonic
Alchorneopsis floribunda	ALCFLO
Alchchornea latifolia	ALCLAT
Buchenavia capitata	BUCCAP
Calycogonium squamulosum	CALSQU
Casearia arborea	CASARB
Cecropia schroeberiana	CECSCH
Cordia borinquensis	CORBOR
Cyrilla racemiflora	CYRRAC
Dacryodes excelsa	DACEXC
Daphnopsis philippiana	DAPPHL
Didymopanax morototoni	DIDMOR
Guarea guidonia	GUAGUI
Haenianthus salicifolius	HAESAL
Inga laurina	INGLAU
Manilkara bidendata	MANBID
Miconia prasina	MICPRA
Miconia tetranda	MICTET
Micropholis garcinaefolia	MIRGAR
Ocotea leucoxylon	OCOLEU
Prestoea montana	PREMON
Psychotria berteriana	PSYBER
Sloanea betreriana	SLOBER
Tabebuia heterophylla	TABHET
Tabebuia rigida	TABRIG

In Figure 6-6, the basal area results are shown for FACET and the recent study at 750 meters. As mentioned previously, the Colorado (CYRRAC) has a significantly higher basal area per FACET in hurricane risk class one (211% higher) and two (124% higher). Conversely, the basal area is much closer for the Colorado in hurricane risk class three (28% higher). *Miconia tetranda* (MICTET) and *Sloanea betreriana* (SLOBER) also have higher basal area values for FACET than the recent study.

Micropholis garcinaefolia (MIRGAR), on the other hand, has higher basal area per the study. In addition, palm (PREMON) has higher basal area per the recent study at all levels of hurricane risk.

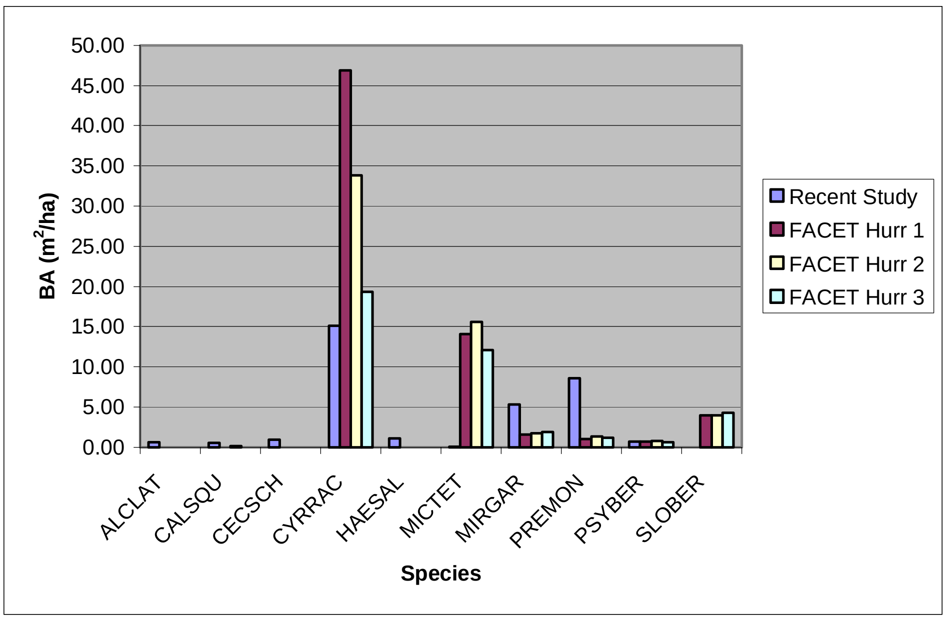

Figure 6-6 Basal Area Comparison Between FACET and Recent Study at 750 meters

In Figure 6-7, the basal area results are shown for FACET and the recent study at 950 meters. The *Tabebuia rigida* (TABRIG) was the dominant species in FACET, but did not show up in the recent study at this elevation. The palm (PREMON) is the most dominant species per the recent study, but shows a lower basal area at all levels of hurricane risk per FACET. *Calycogonium squamulosum* (CALSQU) showed up in the FACET results and not the current study. *Psychotria berteriana* (PSYBER) values were similar for FACET and the recent study. In future work, other species will be included for the Dwarf forest.

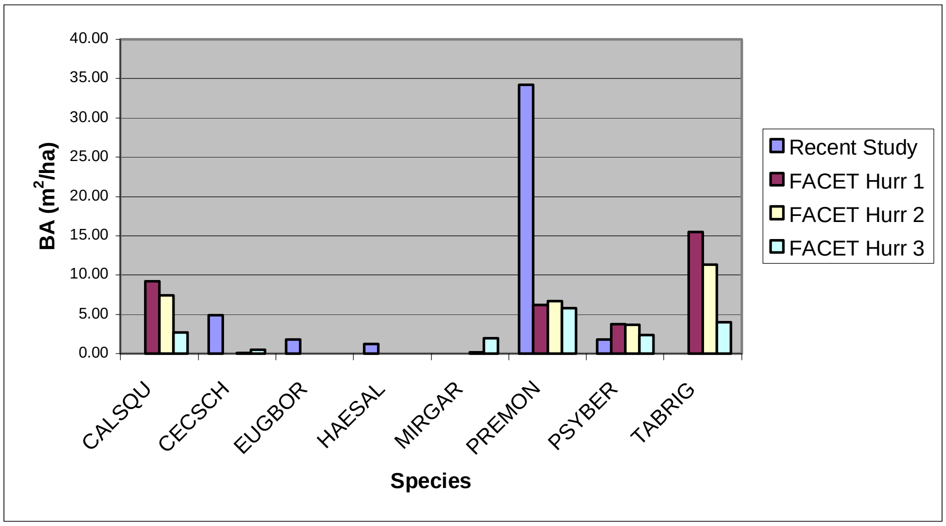

Figure 6-7 Basal Area Comparison Between FACET and Recent Study at 950 meters

This long-term comparison is done using the final value of the run. This snapshot approach can be improved in future work by averaging over a time window of several hundred years in the later part of the run.

Successional Patterns

Recall that species are grouped in five shade tolerance classes which are listed in Table 6-2. These classes are referred to as 1 = very shade-intolerant, 2 = shade-intolerant, 3 = medium shade-tolerant, and 5 = very shade-tolerant.

Table 6-2 Shade Tolerance Classes

Scientific Name	Shade
Cecropia schroeberiana	1
Didymopanax morototoni	1
Casearia arborea	2
Inga laurina	2
Ocotea leucoxylon	2
Tabebuia heterophylla	2
Buchenavia capitata	3
Cyrilla racemiflora	3
Guarea guidonia	3
Manilkara bidendata	4
Micropholis garcinaefolia	4
Calycogonium squamulosum	5
Cordia borinquensis	5
Dacryodes excelsa	5
Daphnopsis philippiana	5
Miconia prasina	5
Miconia tetranda	5
Prestoea Montana	5
Psychotria berteriana	5
Sloanea betreriana	5
Tabebuia rigida	5

Figure 6-8 shows the FACET succession for three of the adaptive species at 350 meters. As can be seen in the figure, *Cecropia schroeberiana* (CECSCH) and *Didymopanax morototoni* (DIDMOR) are very shade-intolerant and dominate early in the successional period. *Psychotria berteriana* (PSYBER), on the other hand, is very shade-intolerant and is more abundant later in the run. The remaining adaptive species are not found at this elevation.

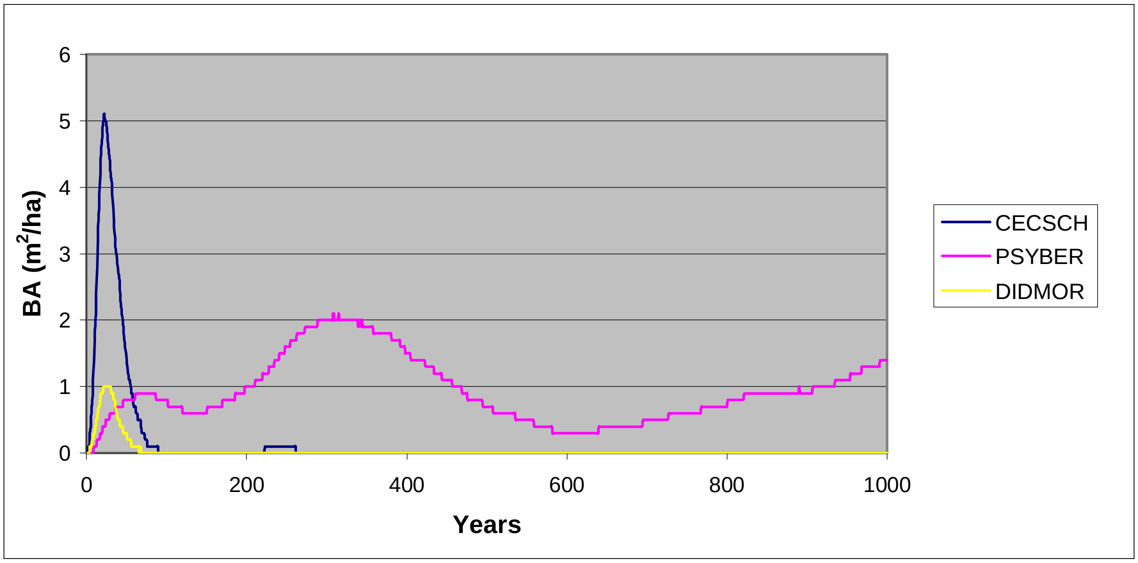

Figure 6-8 Adaptive Species Succession at 350 meters

Figure 6-9 and Figure 6-10 show species' succession at 350 meters. As expected, the very shade-tolerant species, *Dacryodes excelsa* (DACEXC) and *Miconia prasina* (MICPRA), both dominate at the end of the run. Meanwhile, the shade-intolerant species, *Casearia arborea* (CASARB), *Inga laurina* (INGLAU) and *Tabebuia heterophylla* (TABHET), all dominate early on then lose basal area as time (and shade) increases. The medium-shade tolerant species, *Buchenavia capitata* (BUCCAP) and *Guarea guidonia* (GUAGUI), stay at about the same basal area throughout the run as they can tolerate varying amounts of shade.

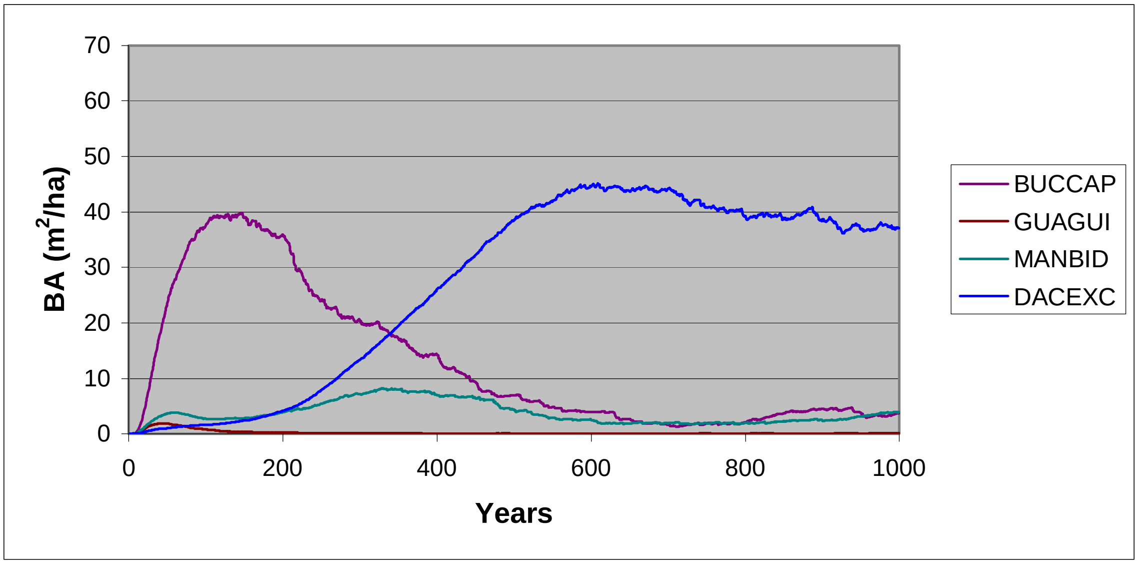

Figure 6-9 Four Tabonuco Species Succession at 350 meters

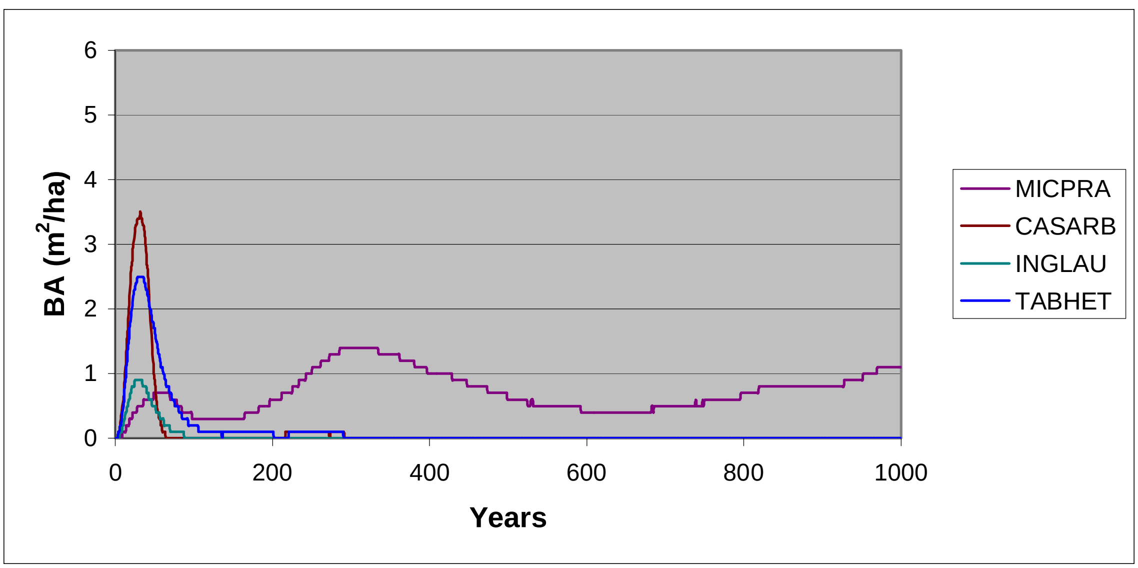

Figure 6-10 Four Tabonuco Species Succession at 350 meters

Figure 6-11 shows adaptive species' succession at 750 meters. As can be seen in the figure, *Cecropia schroeberiana* (CECSCH) and *Didymopanax morototoni* (DIDMOR) are very shade-intolerant and dominate early in the successional period. *Psychotria berteriana* (PSYBER), on the other hand, is very shade-intolerant and is more abundant later in the run. The remaining adaptive species, *Cordia borinquensis* (CORBOR), *Calycogonium squamulosum* (CALSQU), and *Daphnopsis philippiana* (DAPPHL) are very shade-tolerant, but do not grow late in succession. Further work is required to determine why and correct it.

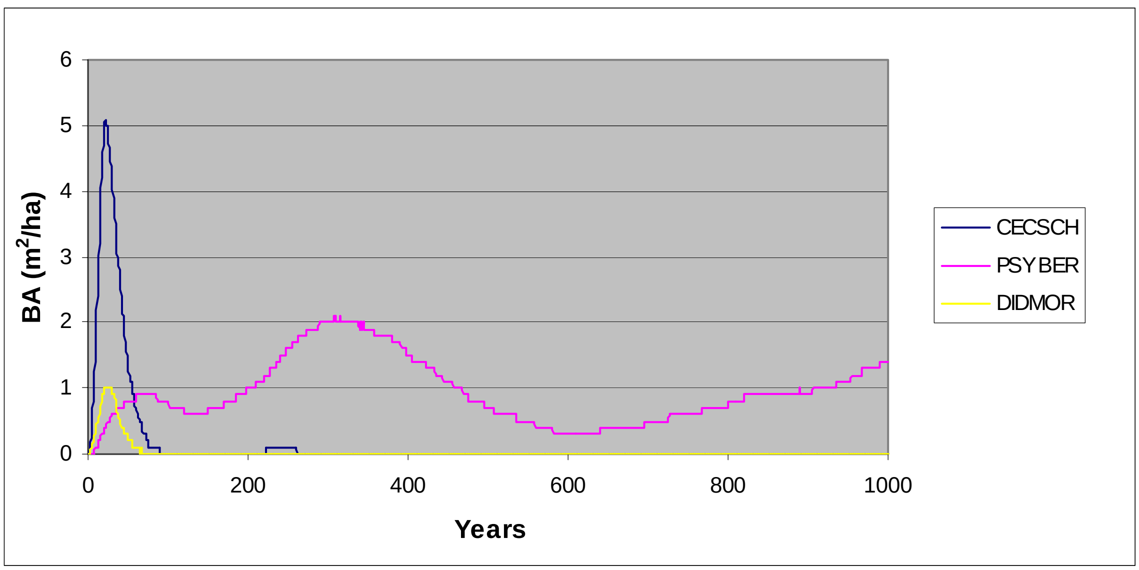

Figure 6-11 Three Adaptive Species Succession at 750 meters

Figure 6-12 shows the Colorado species' succession at 750 meters. *Ocotea leucoxylon* (OCOLEU) is shade-intolerant and shows up early in the succession. *Micropholis garcinaefolia* (MIRGAR) is shade-tolerant, while *Miconia tetranda* (MICTET) and *Sloanea betreriana* (SLOBER) are very shade-tolerant. They cannot, however, compete with the size of the medium-shade tolerant *Cyrilla racemiflora* (CYRRAC), which dominates in basal area at the end of the run.

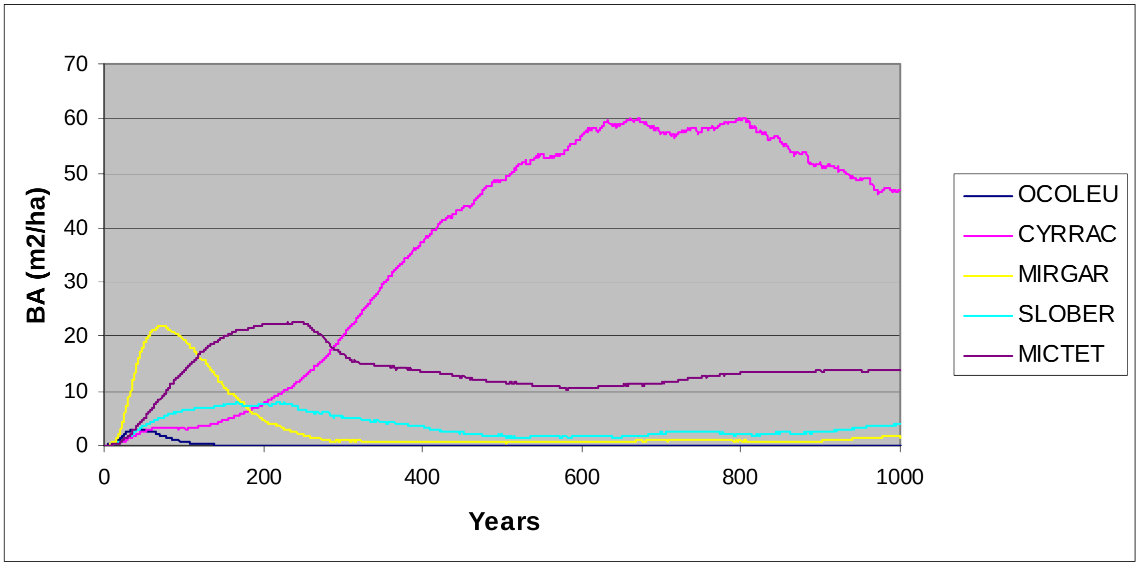

Figure 6-12 Colorado Species Succession at 750 meters

Figure 6-13 shows Dwarf and adaptive species' succession at 950 meters. *Cecropia schroeberiana* (CECSCH) dominates initially as it is an early successional species which is very shade-intolerant. *Psychotria berteriana* (PSYBER) and *Calycogonium squamulosum* (CALSQU) are very shade-tolerant and increase basal area until they are established. The *Tabebuia rigida* (TABRIG) dominates at the end of the run as expected because it is very shade-tolerant and also because it is the only dwarf species with the optimal degree-day parameters.

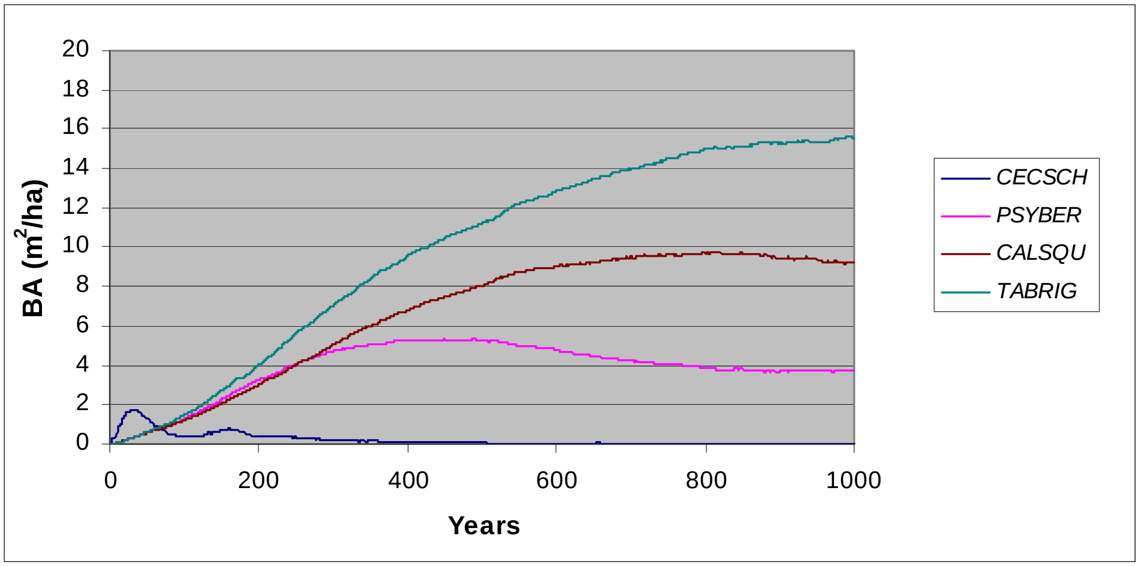

Figure 6-13 Dwarf and Adaptive Species Succession at 950 meters

HURRICANE EFFECTS

Recall that species are grouped in five hurricane susceptibility (as opposed to tolerance) classes (see Table 6-3). We will refer to these five classes as 1 = very susceptible, 2 = susceptible, 3 = medium susceptible, 4 = hurricane tolerant, and 5 = very hurricane-tolerant.

Table 6-3 Species Hurricane Susceptibility (5 is Most Tolerant of Least Susceptible)

Scientific Name	Hurricane Susceptibility
Buchenavia capitata	2
Guarea guidonia	2
Inga laurina	2
Manilkara bidendata	2
Ocotea leucoxylon	2
Sloanea betreriana	2
Calycogonium squamulosum	3
Casearia arborea	3
Cecropia schroeberiana	3
Cordia borinquensis	3
Cyrilla racemiflora	3
Daphnopsis philippiana	3
Didymopanax morototoni	3
Miconia prasina	3
Miconia tetranda	3
Micropholis garcinaefolia	3
Psychotria berteriana	3
Tabebuia heterophylla	3
Tabebuia rigida	3
Dacryodes excelsa	4
Prestoea montana	5

Figure 6-14 shows the adaptive and palm species succession at 350 meters and hurricane risk class 5. The palm (PREMON) is very hurricane-tolerant and recovers the best, as expected. *Cecropia schroeberiana* (CECSCH) peaks right after a hurricane which is this very shade-intolerant species' response to the gap created.

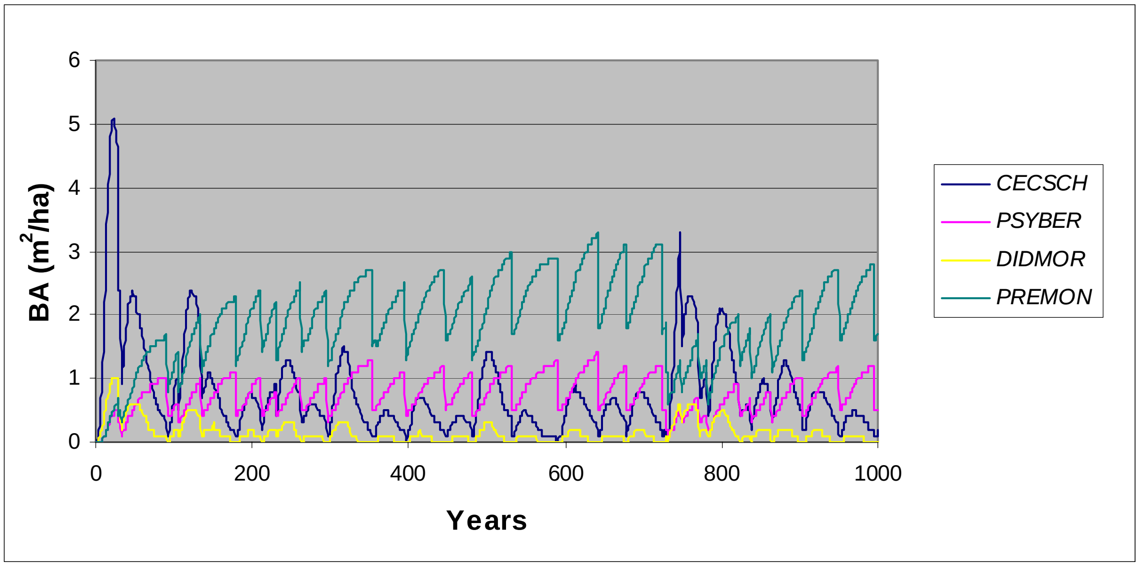

Figure 6-14 Adaptive & Palm Species Succession 350 m Elevation Hurricane Risk Class 5

Figure 6-15 and Figure 6-16 show Tabonuco species' succession at 350 meters and hurricane risk class 5. The *Inga laurina* (INGLAU), *Buchenavia capitata* (BUCCAP), *Guarea guidonia* (GUAGUI) and *Manilkara bidendata* (MANBID) are all susceptible to hurricanes and suffer relatively large basal area losses after a hurricane. *Dacryodes excelsa* (DACEXC) is hurricane tolerant, while *Miconia prasina* (MICPRA), *Casearia arborea* (CASARB), and *Tabebuia heterophylla* (TABHET) are all medium susceptible and suffer relatively less basal area loss following a hurricane.

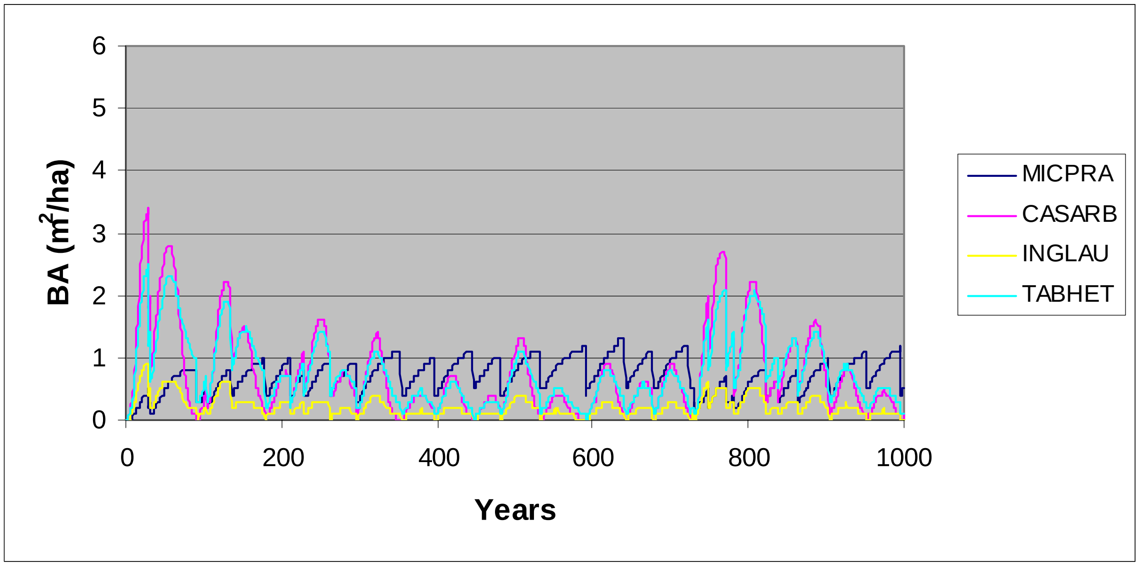

Figure 6-15 Four Tabonuco Species Succession at 350 meters & Hurricane Risk Class 5

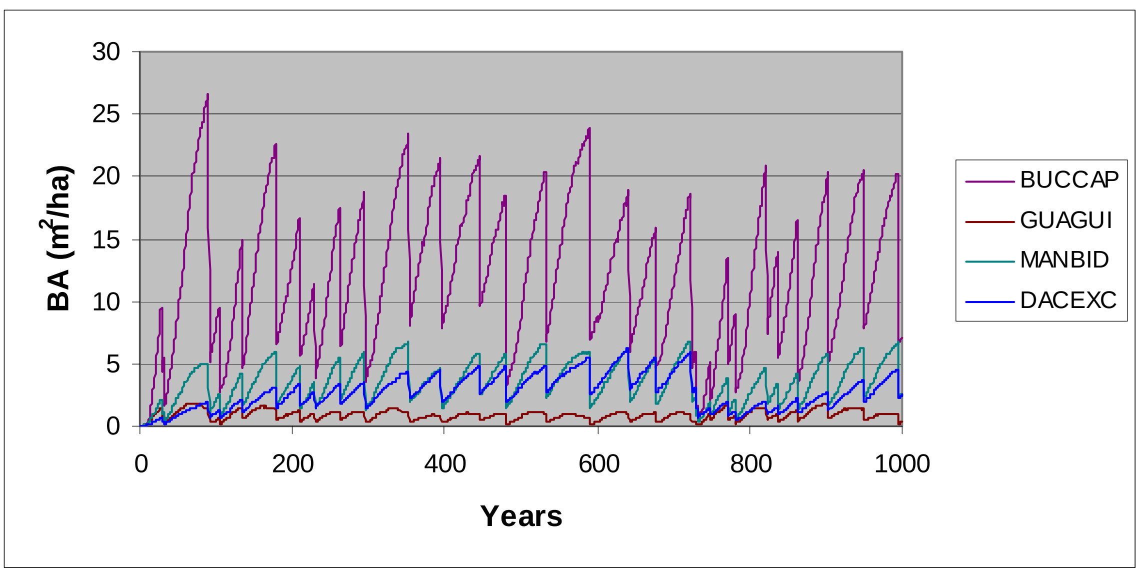

Figure 6-16 Four Tabonuco Species Succession at 350 meters & Hurricane Risk Class 5

Figure 6-17 shows the effect of hurricanes on three representative species. First, *Buchenavia capitata* (BUCCAP) is susceptible to hurricanes and shows the highest percentage basal area loss after a hurricane. Second, *Dacryodes excelsa* (DACEXC) is hurricane-tolerant, and suffers a relatively less percentage basal area loss after a hurricane. Finally, *Prestoea montana* (PREMON) is very hurricane-tolerant and has the least percentage basal area loss after a hurricane.

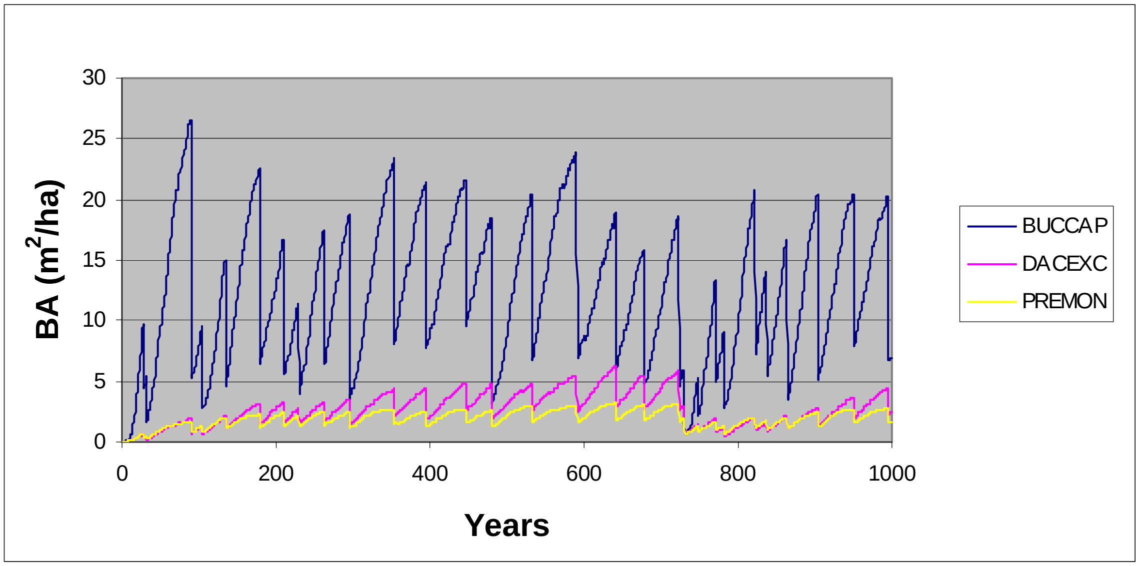

Figure 6-17 Three Species' Response to Hurricanes

Figure 6-18 shows the effect of three different hurricane risk classes on *Prestoea montana* (PREMON). The higher the risk class, the greater the fluctuation due to basal area loss and recovery. However, the resulting basal area in each risk class appears to be at about the same basal area which is a reflection of this species' strong resistance to hurricanes.

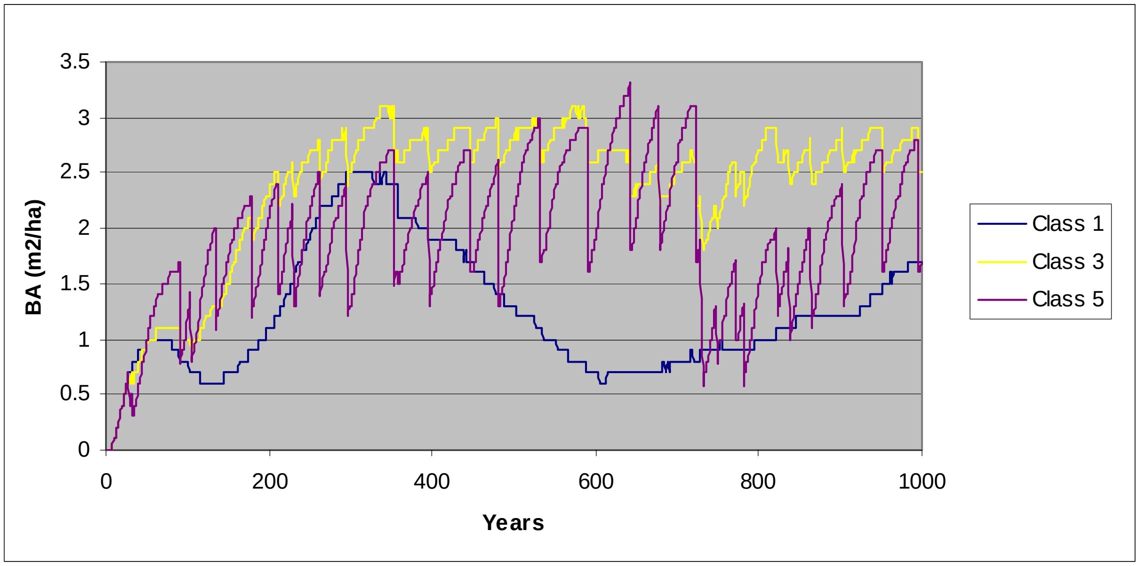

Figure 6-18 Palm Response to Three Hurricane Damage Risk Classes

Conclusions

Two major comparisons of FACET simulation results were performed. The first was for long term representative species along an elevation gradient, and the second one was for stand composition given by dominant species for representative elevations. These comparisons were conducted against a recent study along the Quebrada Sonadora. In addition, successional patterns were analyzed for representative species of each forest type at elevations typical of this forest type. All of these comparisons and analyses were done in terms of basal area and for several hurricane risk classes. Long-term basal area for representative species overestimate the recent study data for low hurricane risk. Upper and lower elevation ranges for each species are close to the ones resulting from the recent study except *Tabebuia rigida* was not found in the recent study above 900 meters.

In regards to stand composition, FACET overestimates basal area for some species and underestimates basal area for others. The overestimation of representative species (*Dacryodes excelsa* and *Cyrilla racemiflora*) is reduced for hurricane risk classes 2 and 3. The recent study was conducted in an area of hurricane risk 2 and 3. *Prestoea montana*, on the other hand, is underestimated by FACET at all elevations which indicates that future work is required to improve the parameter values for this species.

There are no data available to compare simulated and observed successional patterns. The results are as expected given the shade tolerance and growth rates assigned to the individual species. In the Tabonuco forest type, *Dacryodes excelsa*, is the dominant, late-successional species. In the Colorado forest type, *Cyrilla racemiflora* is the dominant, late-successional species. In the Dwarf forest type, *Tabebuia rigida*, is the dominant, late-successional species, followed by the *Calycogonium squamulosum.*

Also, the effect of hurricanes effectively shows the least susceptible species (such as palm) with the least negative effects on basal area, and shade-intolerant species positively affected by hurricane-generated gaps.

CHAPTER 7 MOSAIC

MOSAIC is a forest landscape model based on a semi-Markov transition model (Dr. Miguel Acevedo, University of North Texas, Department of Geography, Denton, TX, 76203). Parameters of MOSAIC can be estimated by scaling-up the FACET succession model. FACET is a gap model derived as a relief-sensitive version of the spatially-explicit ZELIG gap model (Urban et al., 1991, Urban and Shugart, 1992) (Dean L. Urban, FACET and ZELIG version 2, Department of Forest Sciences, Colorado State University, Fort Collins, CO 80523). The landscape is represented as a collection of regions each representing a homogeneous facet. Regions can be irregular polygons or cells in a regular grid. The size of each landscape region or cell is scalable from one to many FACET grids. In this thesis, we used cells of size 30 x 30 m corresponding to the resolution of the original DEM. Terrain type for each MOSAIC cell is given by a combination of five environmental factors such as those given in Table 5-5. Once the MOSAIC parameter values are estimated by SEMAPAR for a selected set of terrain types (280 in this thesis) the model is executed for the entire landscape by finding for each cell the closest match between terrain conditions to one of the calibrated set of terrain types.

Forest condition was classified into different cover types, as discussed in Chapter 5. This is important for land use management, such as maintaining mature forest. One recent study shows that forest regeneration was greatest close to remnant patches of mature (dense) forest (Thomlinson et al., 1996).

Figure 7-1, Figure 7-2, and Figure 7-3 show the elevation, soil, and hurricane GIS files used as input for MOSAIC. Each cell of these files is classified into one of the categories listed in Table 5-5. For ease of reference, Table 7-1 shows the cover types as discussed in Chapter 5.

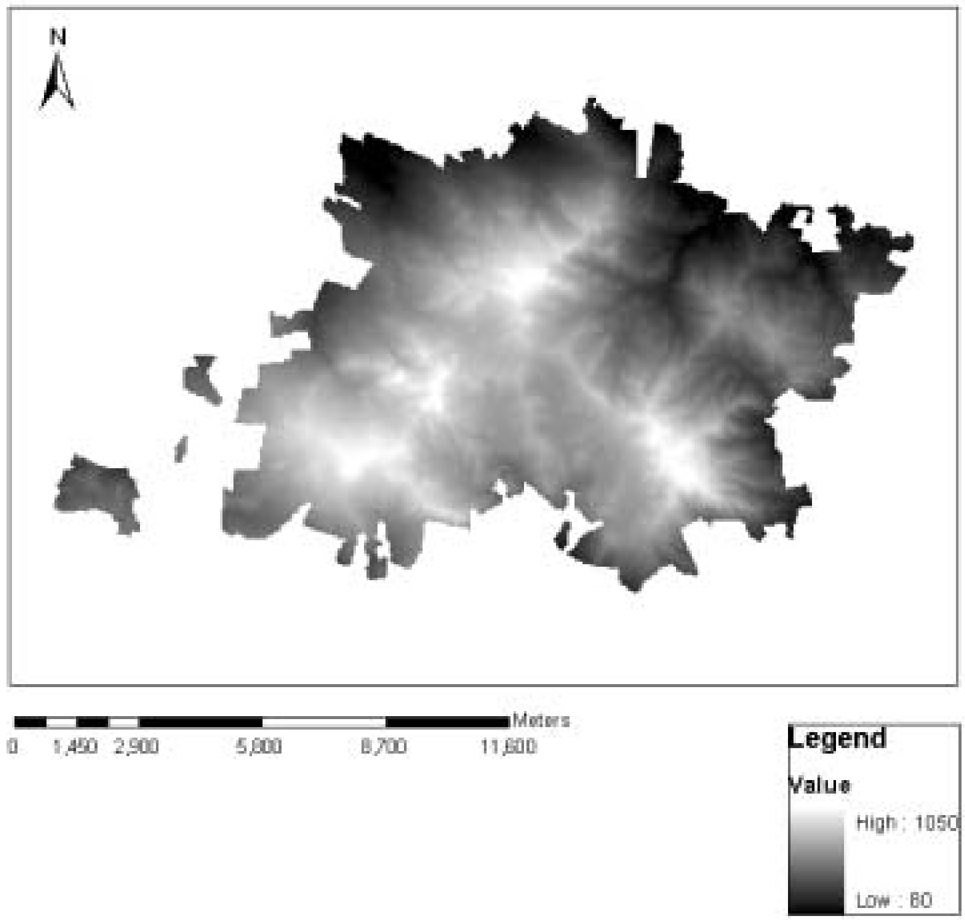

Figure 7-1 Elevation GIS File

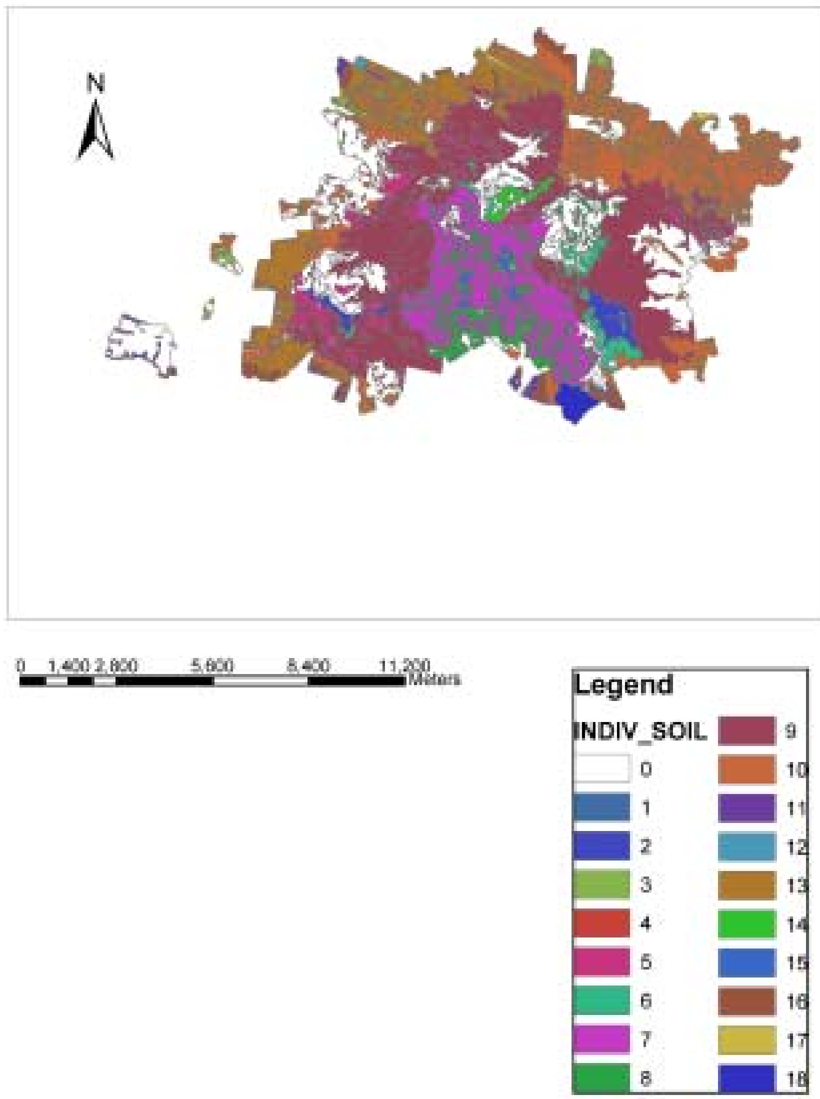

Figure 7-2 Soil GIS File

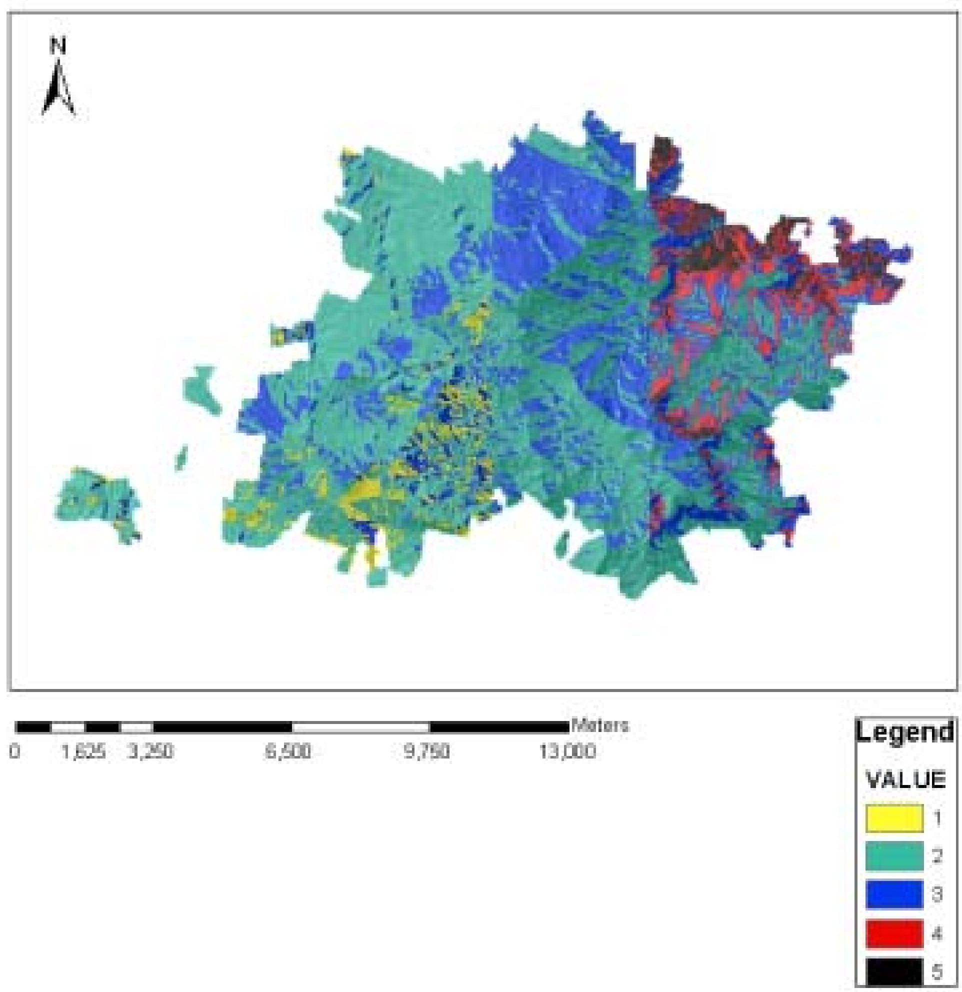

Figure 7-3 Hurricane Risk Class GIS File

Table 7-1 States and Respective Cover Types

State or Cover Type	Canopy Height	BA Dominant Species
1	L	Gap
2	L	Adaptive
3	L	Tabonuco
4	L	Colorado
5	L	Palm
6	L	Dwarf
7	M	Adaptive
8	M	Tabonuco
9	M	Colorado
10	M	Palm
11	M	Dwarf
12	H	Adaptive
13	H	Tabonuco
14	H	Colorado
15	H	Palm
16	H	Dwarf

Long-Term Mosaic Output

Figure 7-4, Figure 7-5, Figure 7-6, and Figure 7-7 are MOSAIC output maps at the end of a 900-year run that show the areas of the LEF covered by low Dwarf forest (state 6), medium adaptive forest (state 7), medium Colorado forest (state 9), high Tabonuco forest (state 13), and high Palm forest (state 15). The Colorado and Tabonuco forests appear to be growing at the proper elevation. Conversely, Adaptive forest seems to be improperly dominating the areas where Dwarf forest should be found. In addition, Palm forests appear to be scattered, as is found in the LEF, but the values are low (less than 30%).

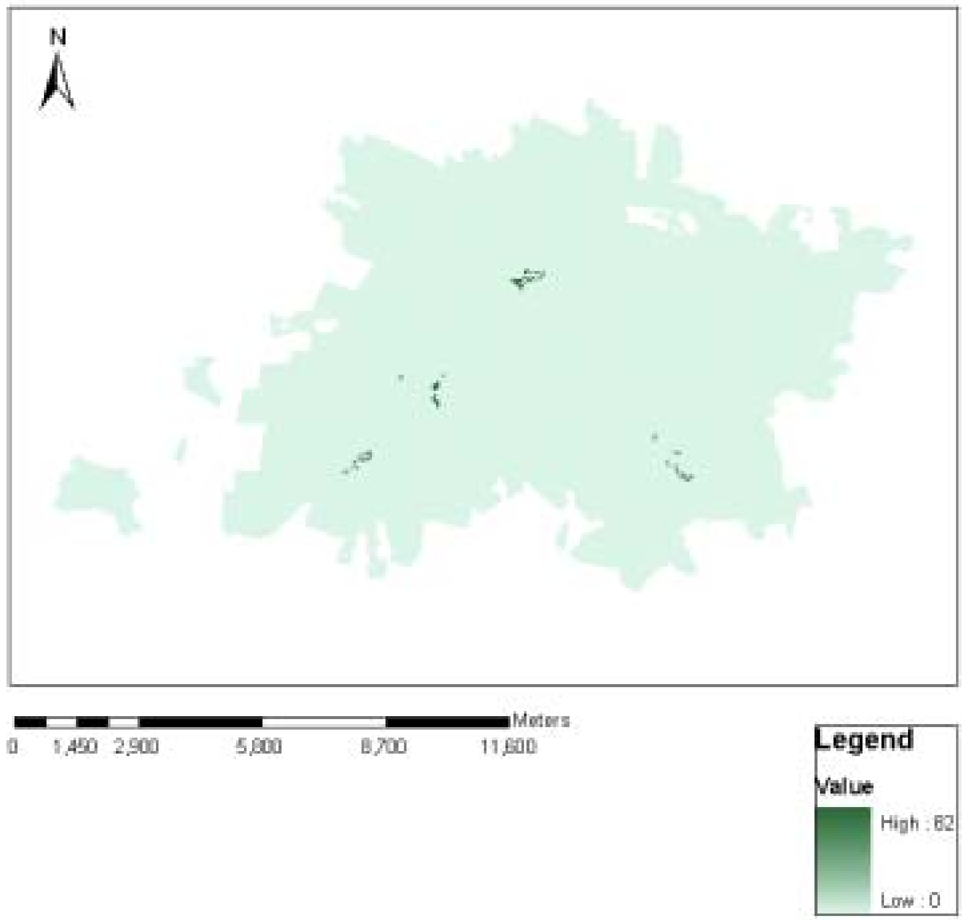

Figure 7-4 State 6 (Low Dwarf) at Time 900 Years

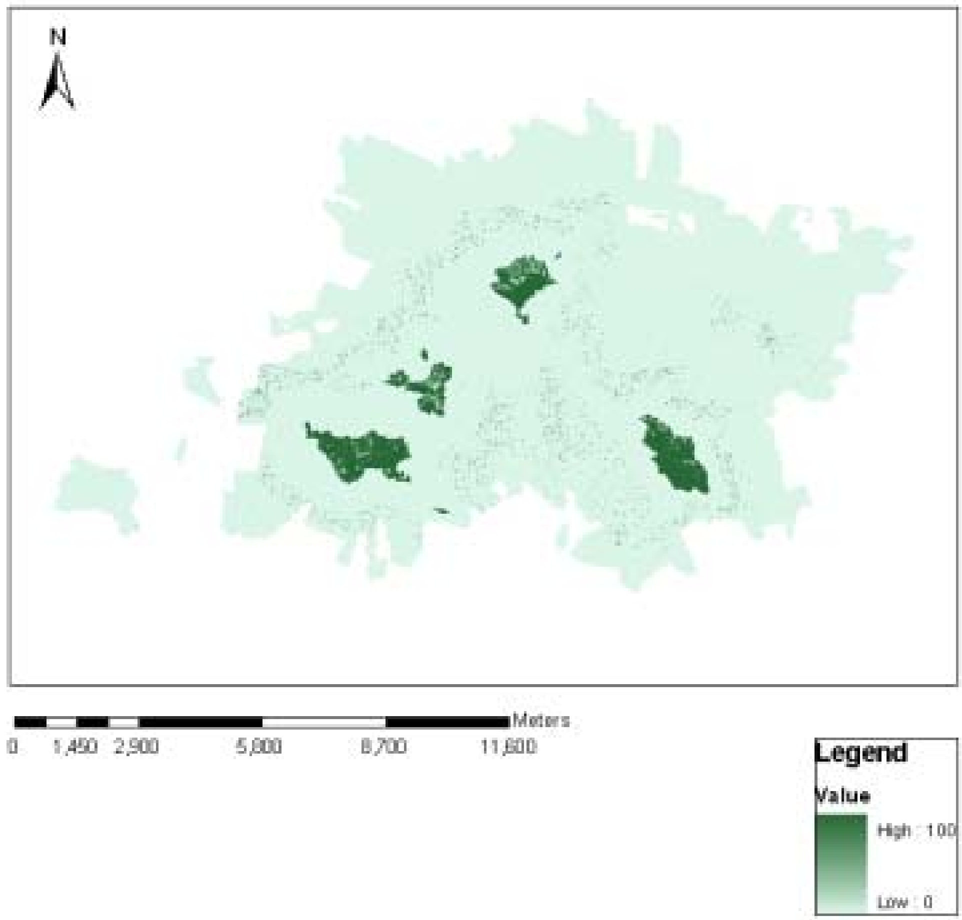

Figure 7-5 State 7 (Medium Adaptive) at Time 900 Years

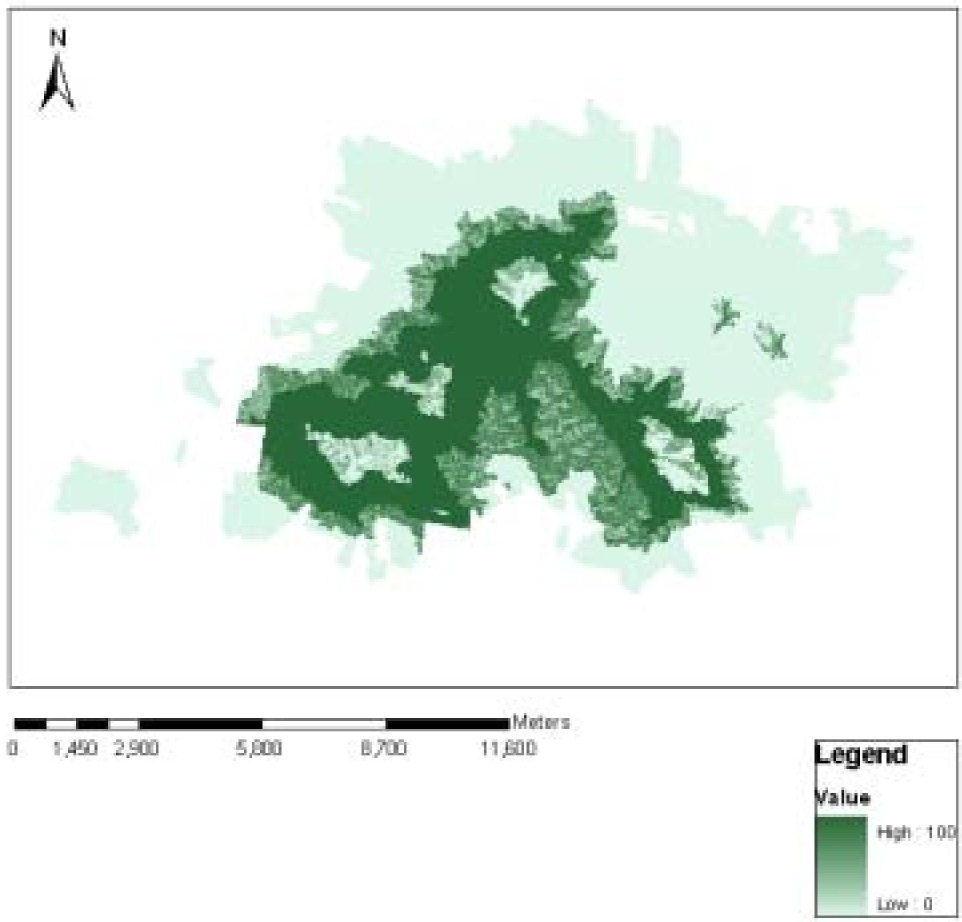

Figure 7-6 State 9 (Medium Colorado) at Time 900 Years

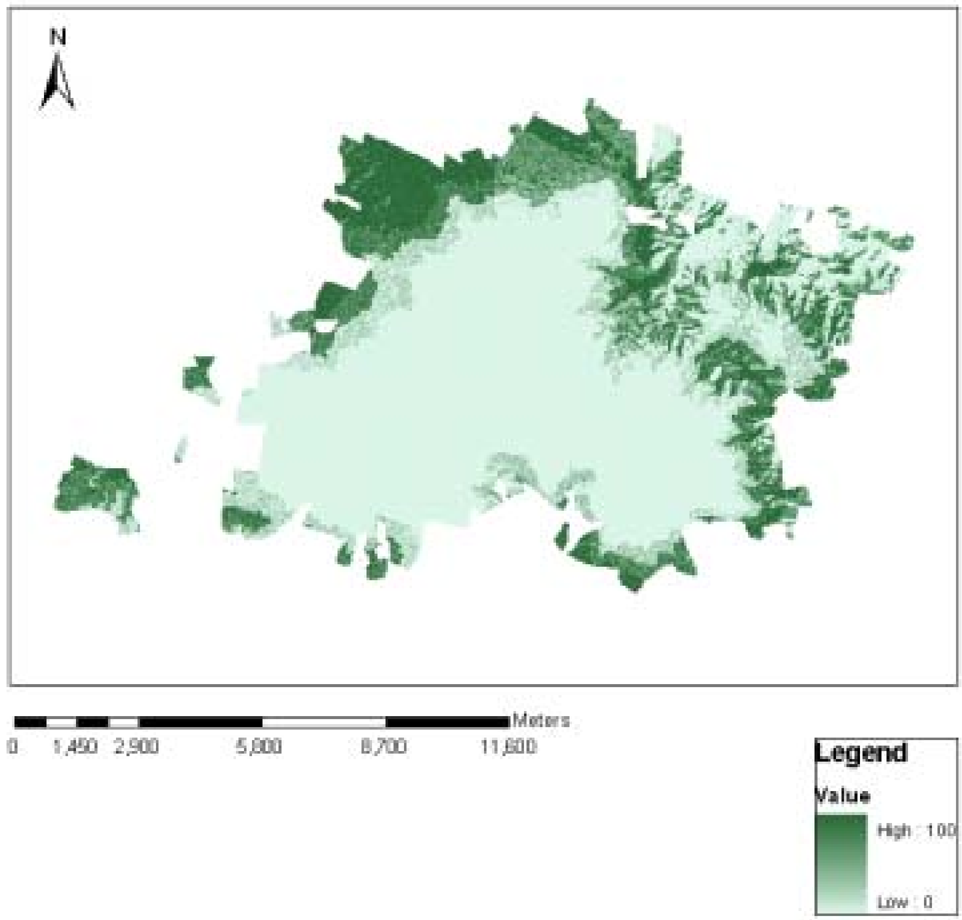

Figure 7-7 State 13 (High Tabonuco) at Time 900 Years

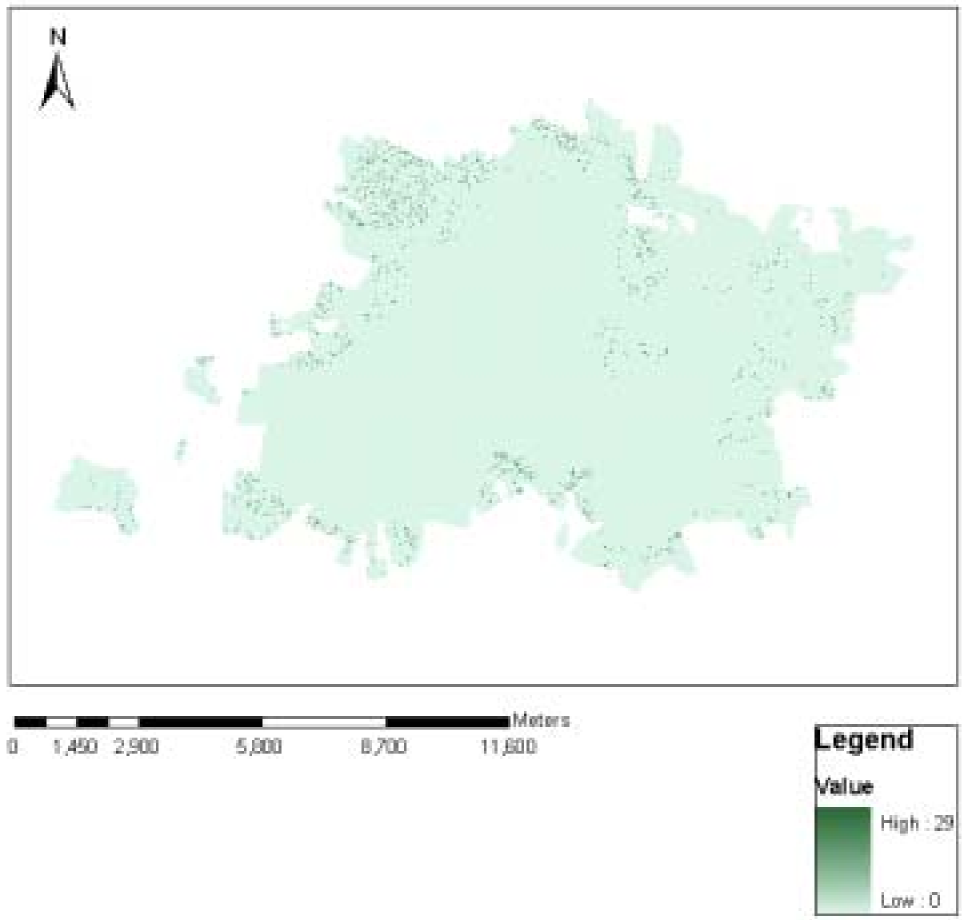

Figure 7-8 State 15 (High Palm) at Time 900 Years

Transition Patterns

In this section, we examine the transition probability matrices estimated by SEMAPAR at some selected terrain types. A transition graph is drawn to illustrate the patterns.

Figure 7-9 shows the percentage of forest type that transition from one state to another at 350 meters for hurricane risk class 1. From the initial gap state, 72% transitions to low adaptive, and 28% to low Tabonuco. All of the low Adaptive then transitions to low Tabonuco. From there, 15% transitions back to low Adaptive, and 85% to medium Tabonuco; 8% then stays medium, while 92% transitions to high Tabonuco. Finally, 100% of the forest stays high Tabonuco, as expected.

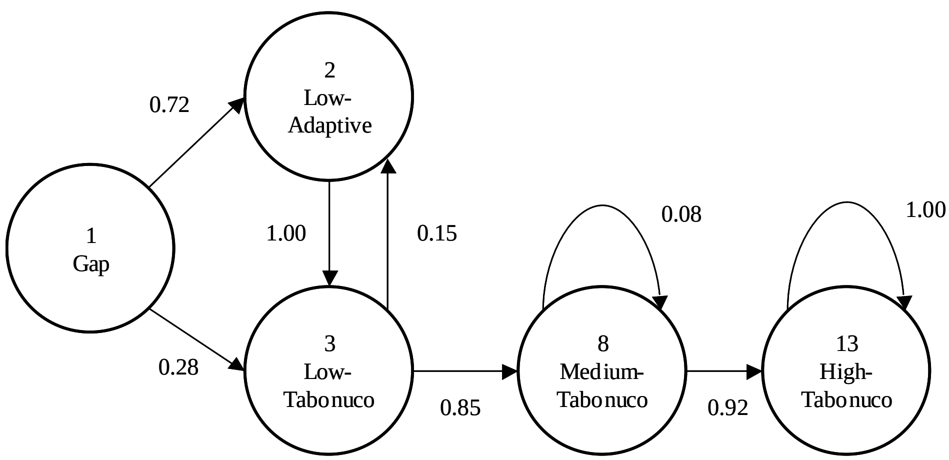

Figure 7-9 State Percentage Transitions Elevation 350 m Hurricane Risk Class 1

Figure 7-10 illustrates the state transitions at 350 meters for hurricane risk class 5. This diagram shows transitions to Palm and medium Adaptive states, which do not appear during the run for hurricane risk class 1. This appears correct as palms and some of the adaptive species, notably Cecropia, do well under hurricane regimes.

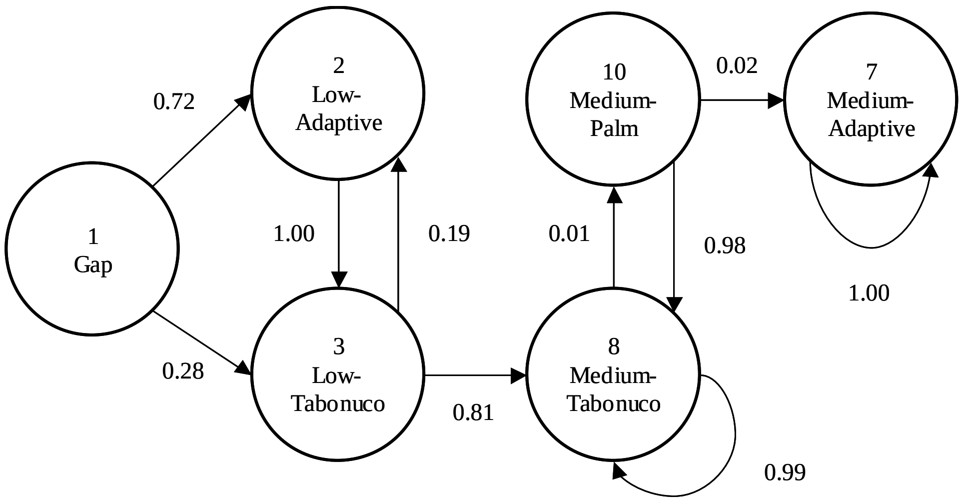

Figure 7-10 State Percentage Transitions Elevation 350 m Hurricane Risk Class 5

Figure 7-11 shows the state percentage transitions at elevation 750 meters for hurricane risk class 1. Initially, 98% of the forest type moves from gap to low Adaptive. From there, however, most of the forest type converges to low Colorado, then to medium Colorado, as expected.

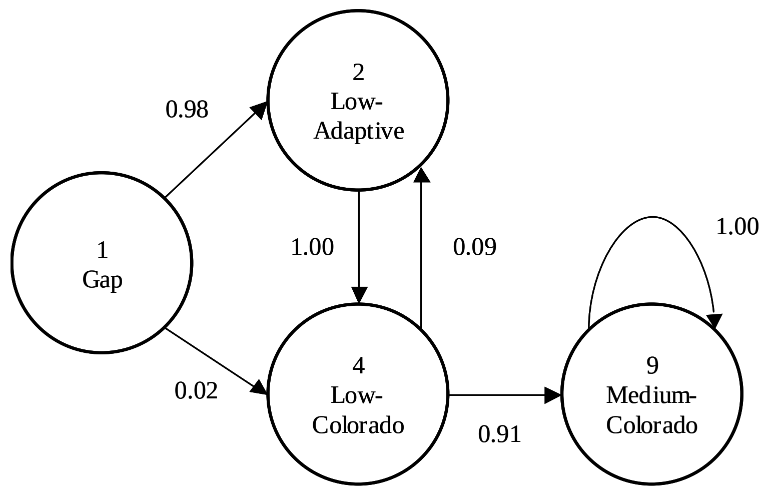

Figure 7-11 State Percentage Transitions Elevation 750 m Hurricane Risk Class 1

Figure 7-12 shows the state percentage transitions at 750 meters for hurricane risk class 5. Unlike the same run at hurricane risk class 1, the forest type ends up one-third medium Adaptive due to the shade-intolerant species of the Adaptive forest type which prefer the gaps created by hurricane damage.

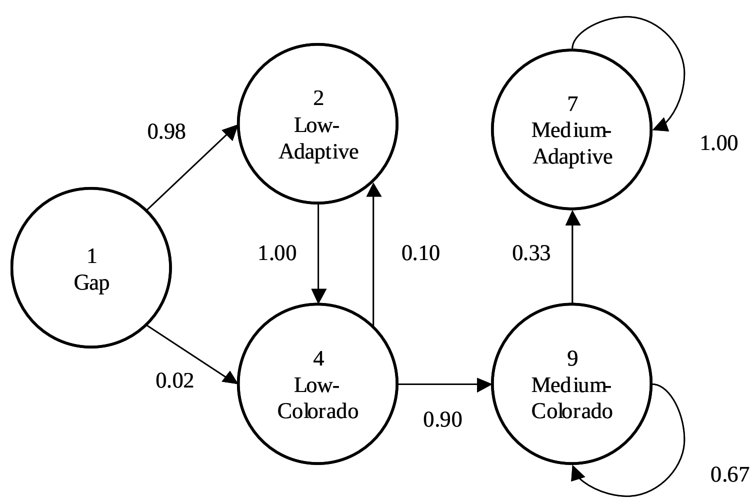

Figure 7-12 State Percentage Transitions Elevation 750 m Hurricane Risk Class 5

The last state percentage transition for elevation 1050 meters and hurricane risk class 1 is shown in Figure 7-13 80% of the resulting cover type is medium Dwarf, while 20% is medium Adaptive.

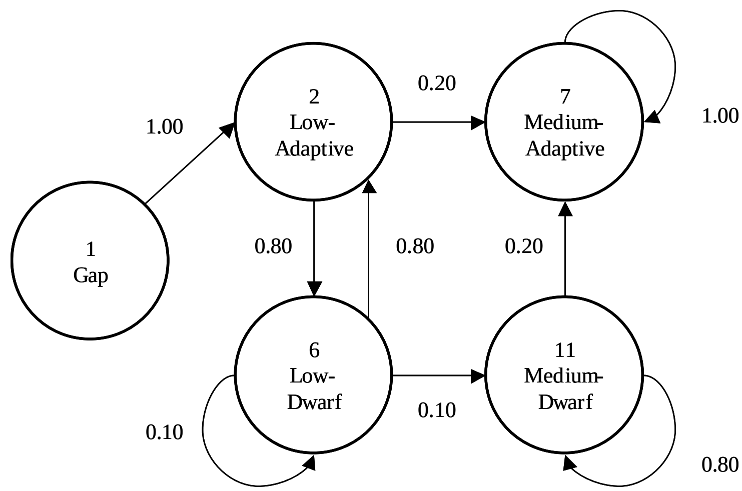

Figure 7-13 State Percentage Transitions Elevation 1050 m Hurricane Risk Class 1

FACET-MOSAIC

Figure 7-14 shows a comparison of percentage basal area for high Tabonuco forest resulting from MOSAIC and FACET runs. As the graph illustrates, the results are nearly identical, meaning the probabilistic, landscape MOSAIC run nearly matches the individual GAP model. Figure 7-15 shows a relatively good match for the MOSAIC and FACET runs for the Colorado forest type. While Figure 7-16 does not show such a close match, it does show that MOSAIC results in a “smoothing out” of the FACET run.

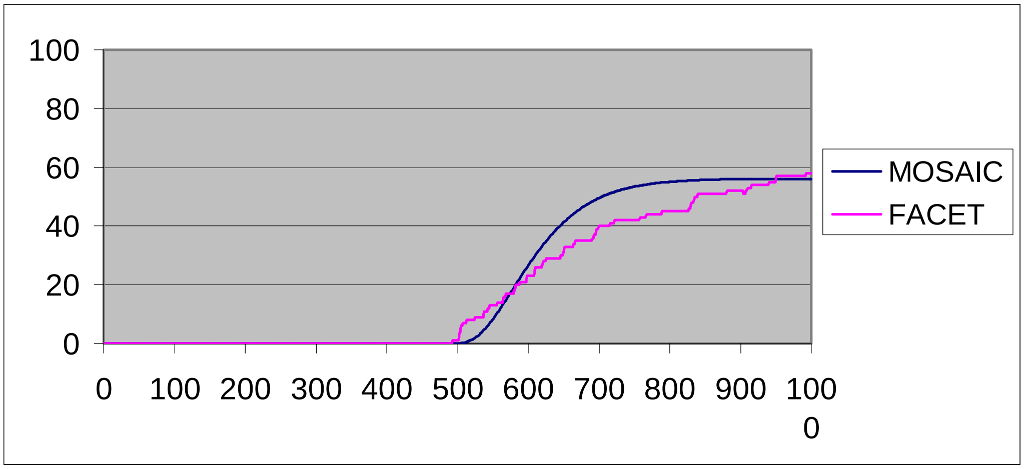

Figure 7-14 MOSAIC vs. FACET % Cover High Tabonuco Cover Type at Elevation 350 m & Hurricane Risk Class 3

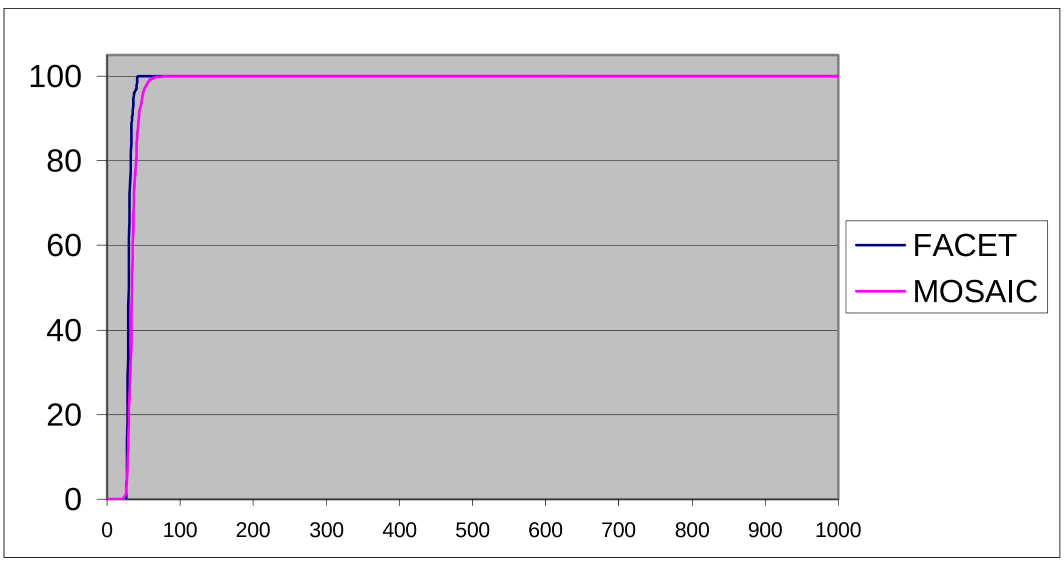

Figure 7-15 MOSAIC vs. FACET % Cover Medium Colorado Cover Type at Elevation 750 m & Hurricane Risk Class 2

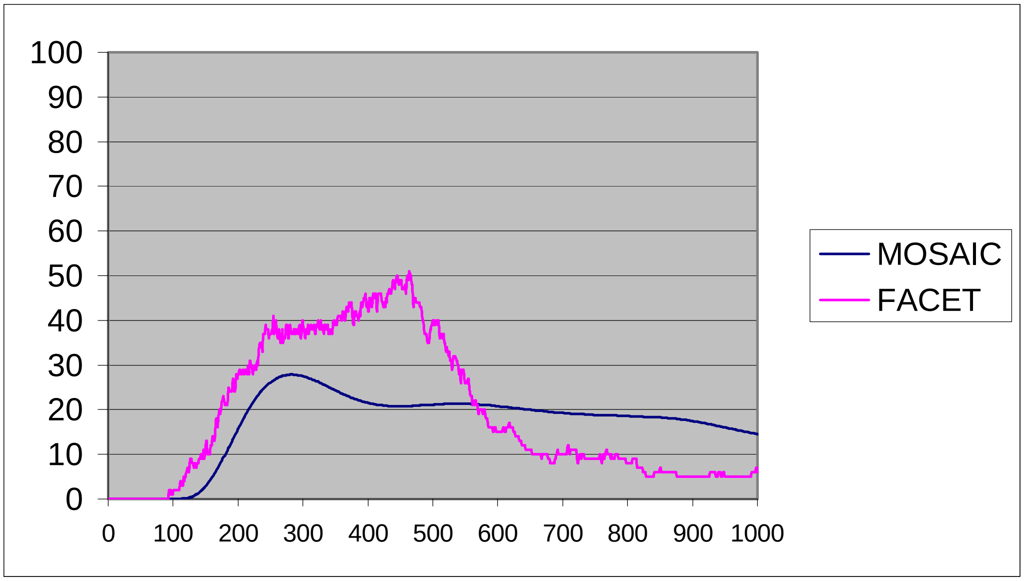

Figure 7-16 MOSAIC vs. FACET Percent Cover Low Dwarf Cover Type at Elevation 1050 m & Hurricane Risk Class 1

MOSAIC Dynamics

The following figures are prepared by draping the MOSAIC output map on a 3D view of the elevation maps. Figure 7-17 shows the progression of the low Dwarf forest (state 6) at 100, 300, 500, and 700 years. As mentioned previously, the Dwarf forest is only dominating at the highest elevations (around 1000 meters) and not at elevations between 900 and 1000 meters.

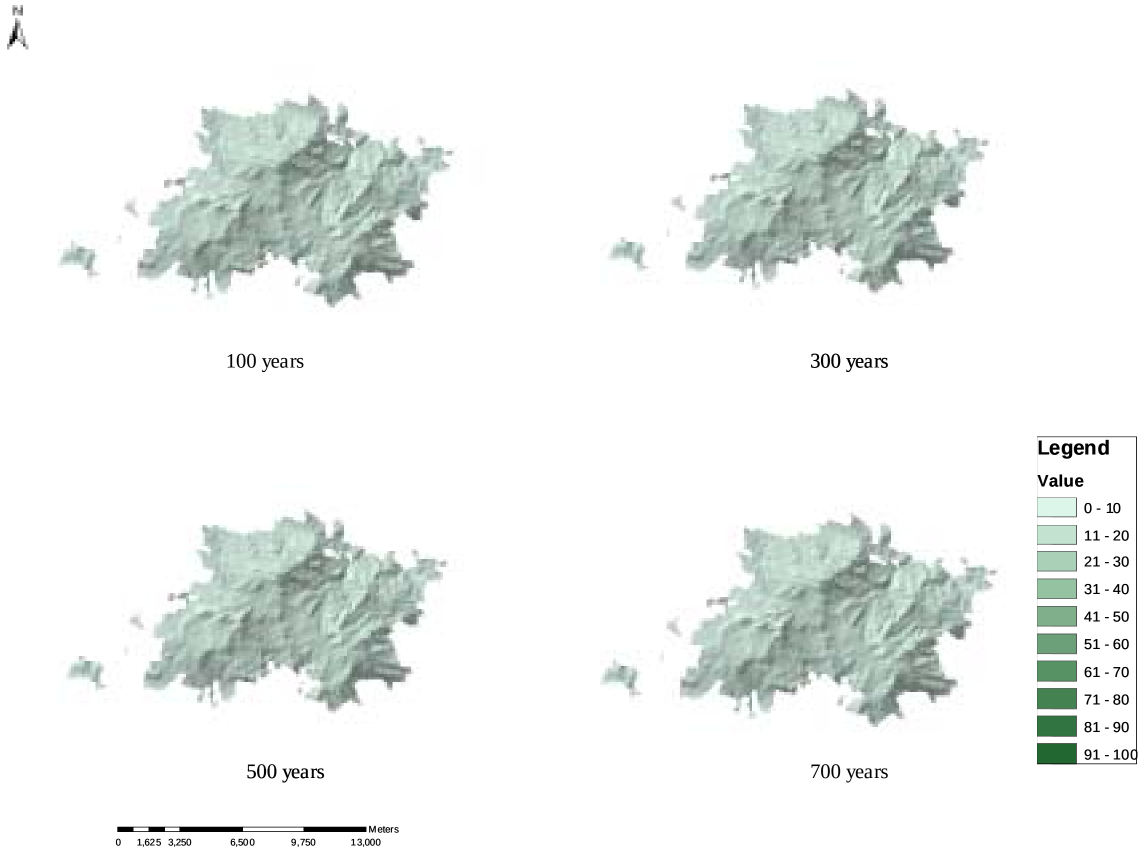

Figure 7-17 State 6 (Low Dwarf) at 100, 300, 500, and 700 Years

Figure 7-18 shows the progression of the medium Adaptive forest (state 7) at 100, 300, 500, and 700 years. As discussed above, this forest type is dominating in areas where the Dwarf forest should be the primary species between 900 – 1000 meters.

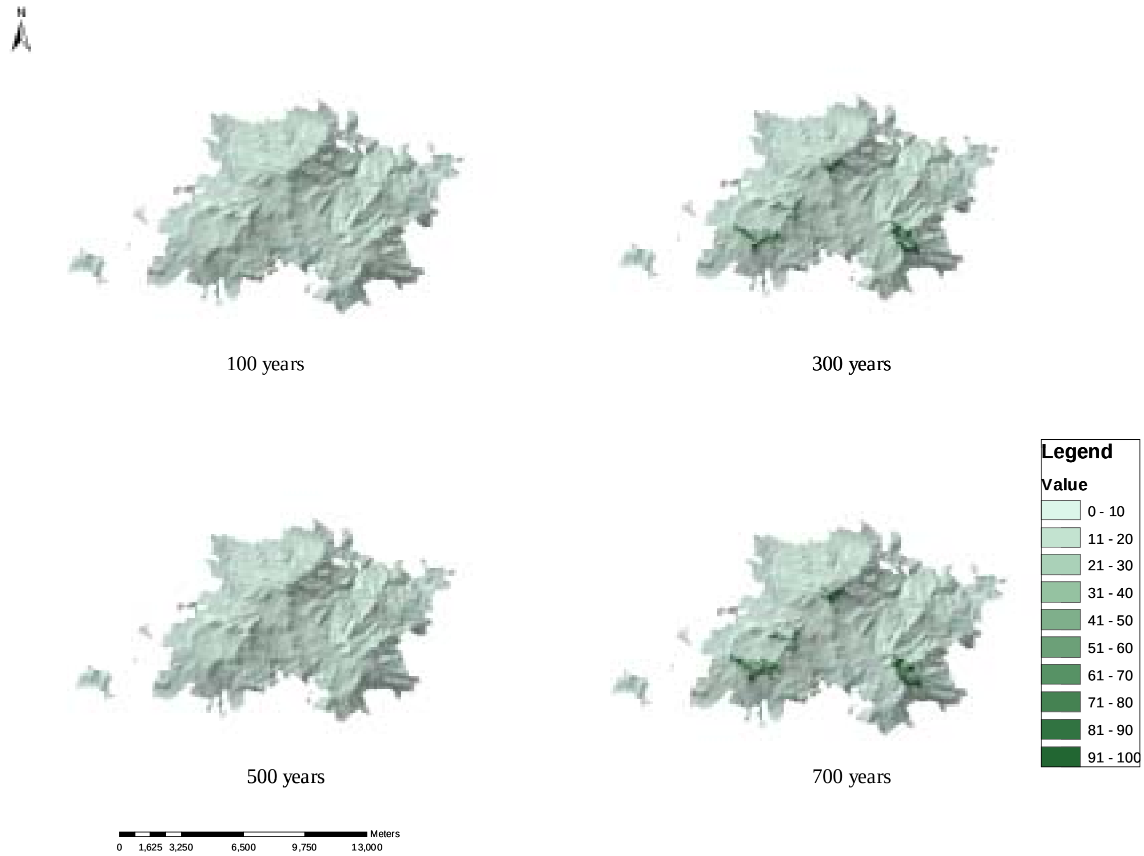

Figure 7-18 State 7 (Medium Adaptive) at 100,300, 500 and 700 Years.

Figure 7-19 shows the growth of the medium Colorado forest (state 9) at 100, 300, 500, and 700 years. This forest type seems to dominate at too wide of an elevation range early, but then appears to fall nicely within its expected elevation range.

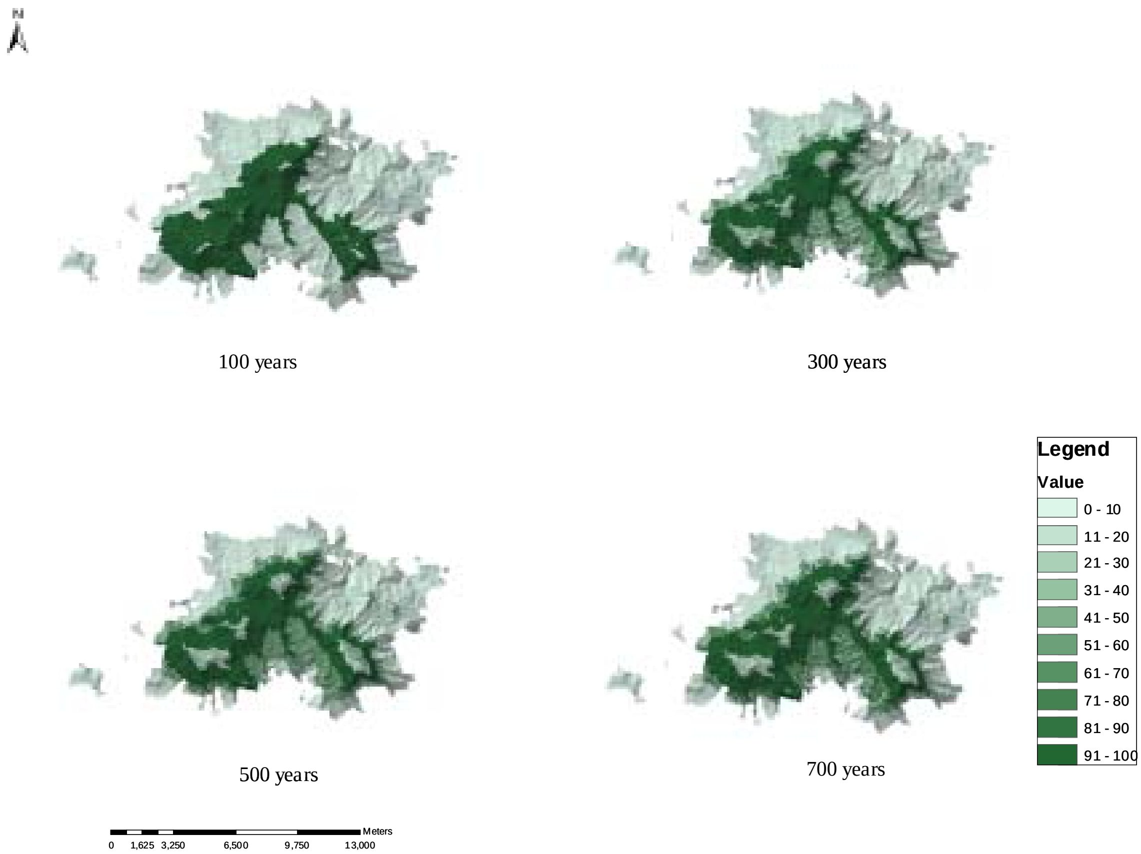

Figure 7-19 State 9 (Colorado) at 100, 300, 500, and 700 Years

Figure 7-20 illustrates the progression of the high Tabonuco forest type (state 13) at 100, 300, 500 and 700 years. This forest type does not show significantly until after year 500 as it is a relatively slow-growing tree. At the end of the run, the Tabonuco is appropriately dominating at the lower elevational ranges of the LEF.

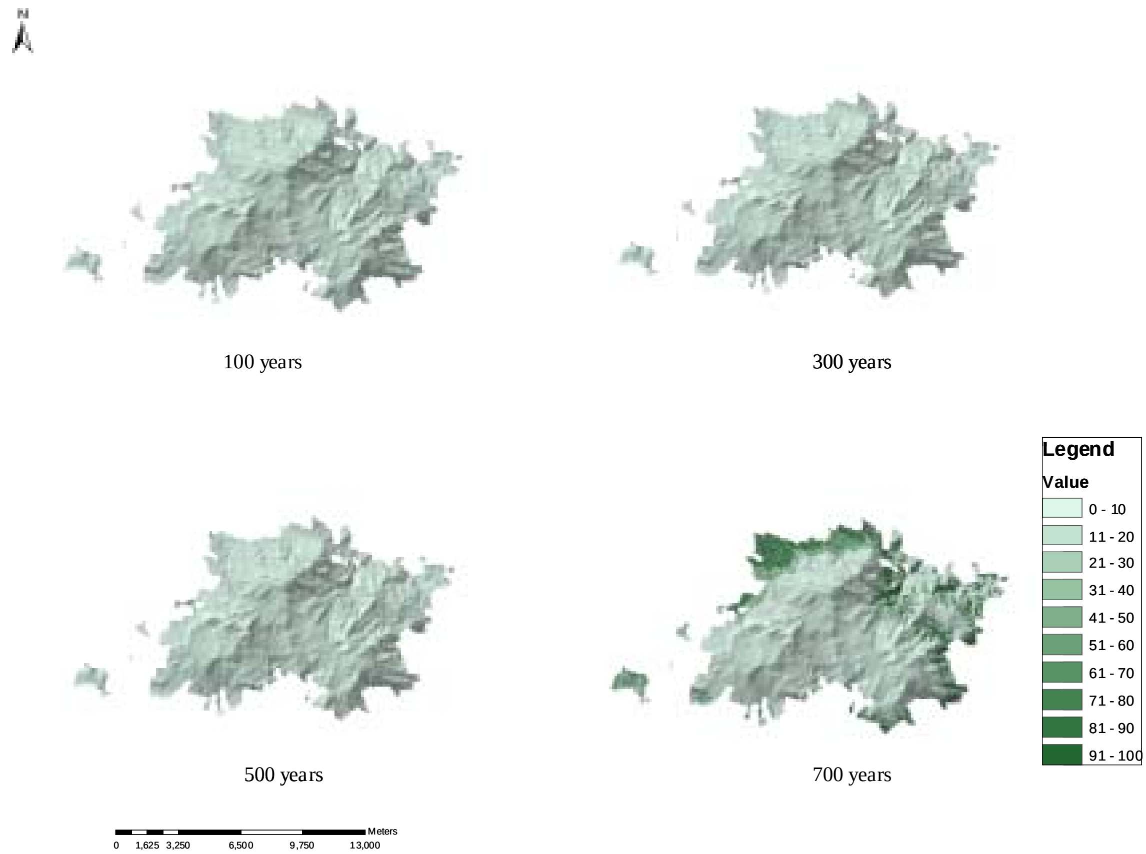

Figure 7-20 State 13 (High Tabonuco) at 100, 300, 500, and 700 Years

Figure 7-21 shows the succession of the high Palm forest type (state 15) at 100, 300, 500, and 700 years. This forest type does not appear until year 700, and only exists in small patches. Further work is required to determine why this model does not project the palm forest to be more abundant.

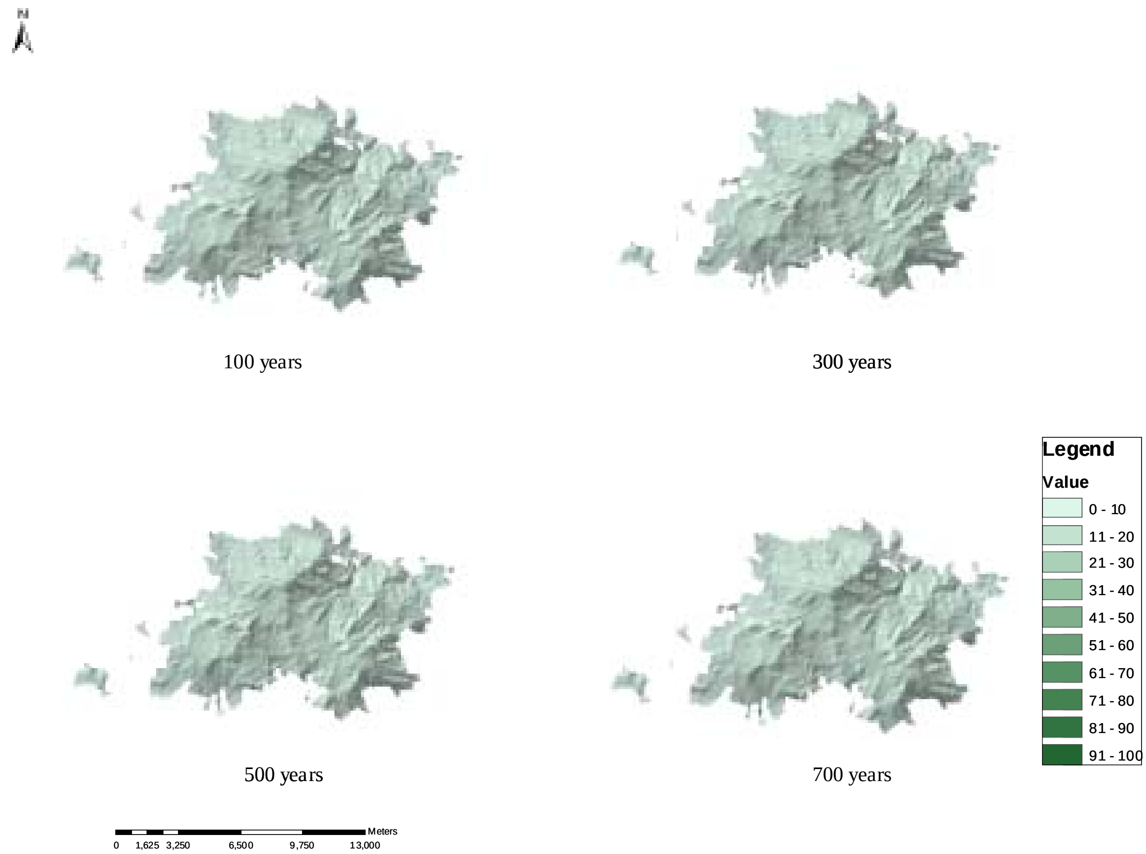

Figure 7-21 State 15 (High Palm) at 100, 300, 500, and 700 Years

Conclusions

We analyzed several types of results. One is the long-term maps for mature states. These were selected according to tree height for different forest types: high Tabonuco, medium Colorado, low Dwarf, high Palm, and medium Adaptive. The next type is transition pattern represented by mosaic transition matrices calculated by SEMAPAR. Another type of result is a comparison of state dynamics from FACET and

MOSAIC. The final type are successional maps for the same set of states used for the long-term maps.

In regard to the long-term maps for mature state, it appears that the Colorado and Tabonuco forests are dominating at proper elevation ranges. However, Adaptive forests seem to be dominating areas of the Dwarf forest elevation range (Dwarf forest only appears at the upper part of its elevation range). Also, medium Adaptive forests are dispersed with higher values at mid-elevations where medium Colorado and high Tabonuco are also present. In addition, Palm forests are found in small patches and not as prevalent as literature indicates. Further work will address these issues.

Transition patterns were examined at three elevations representative of forest types: 350, 750, and 1050 meters. Two hurricanes risk classes were analyzed for 350 and 750, but only one risk class at 1050 because there is generally not high hurricane risk at higher elevations. At 350 meters and low hurricane risk, there is a successional sequence from low to medium to high tabonuco, as expected. At the same elevation and higher hurricane risk, the sequence stops at medium tabonuco and there is medium Palm and medium Adaptive states resulting from the hurricane disturbance. There is a successional sequence from low to medium Colorado for both low and high hurricane risk. However, for high risk, there are transitions from medium Colorado to medium Adaptive. At 1050 meters elevation, there is a successional sequence from low to medium Dwarf, but there is also a sequence from low to medium adaptive. So the effect is a mix of medium Dwarf and medium Adaptive.

Comparisons of percent cover produced by MOSAIC and FACET were performed for 350, 750, and 1050 meters elevation for the most common hurricane risk class at each elevation. The results show a relatively good match, especially for medium Colorado cover type at 750 meters. At 1050 meters, MOSAIC tracks FACET well for the early part of the simulation, but smooths out the large fluctuations in the latter part.

For the sake of brevity, not all simulation years are shown for the successional maps. We selected 100, 300, 500, and 700 years for the same set of states for the long-term maps. Tabonuco's long-term distribution is established mid-way through the 1,000 year run. The Colorado forest type distribution establishes in the early part of the run from mid- to high- elevations. Low Dwarf distribution is limited to high elevations and establishes itself before mid-way through the 1,000 year run. Medium Adaptive also shows higher values at higher elevations as discussed before and this pattern is established before mid-way in the run. High Palm shows up after mid-way through the run and is scattered too sparsely.

CHAPTER 8 CONCLUSIONS

The original FACET species file contained mostly Tabonuco forest species. . FACET is a gap model derived as a relief-sensitive version of the spatially-explicit ZELIG gap model (Urban et al., 1991, Urban and Shugart, 1992) (Dean L. Urban, FACET and ZELIG version 2, Department of Forest Sciences, Colorado State University, Fort Collins, CO 80523). Upper elevational species were successfully added, including a Dwarf forest species (*Tabebuia rigida*). Maximum diameter, age, and growth rate for these species were estimated, and minimum and maximum degree days were determined. Allometric coefficients were based on diameter and height of individual trees for the Colorado forest. Future work will involve obtaining individual tree measurements for the Tabonuco species. Species response to soil fertility was not determined, but is required in future work.

Temperature, precipitation, and solar radiation data were obtained for the site file and appear reasonable when compared with available data. A lapse rate was successfully calculated based on available research which accounts for precipitation changes with elevation.

For soil measurements, 13 of 18 LEF soil types had data available to make an estimation of soil moisture and fertility. Field capacity and wilting point by layer was based on percent sand, clay, and silt. For soil fertility, missing information included organic matter, pH, and contents of coarse fragments. However, all but five had effective depth and CEC data, which were assigned a combined index value and ranked. For the remaining five, estimates were made based on matching soil descriptions. Further work includes obtaining more complete soil data to better estimate soil fertility and implement FACET's species' response to soil fertility. The last soil measurement, fast-flow fraction, was calculated from clay percentage for each soil series and scaled for FACET.

FACET's calculation of solar radiation appeared to be overestimated, so data was obtained and input into the model. Also, PET was understated by FACET, so it was determined that a correction factor should be added. After adding this factor, PET results seem appropriate for the LEF.

One of the ways FACET was extended for the LEF was the inclusion of hurricanes. The user decides minimum and maximum hurricane recurrence, then FACET randomly generates hurricane occurrence with a uniform distribution based on these inputs. With better statistics on hurricane frequency, this uniform distribution will be replaced with a more appropriate calculation in future work.

FACET now randomly generates a hurricane intensity factor based on a scale of 1 – 5, with equal probabilities. Future work will include different probabilities for different intensities and adding a sliding scale for time between hurricanes as higher-intensity storms do not occur as often as low-intensity. A multiplier effect was also added based on damage due to wind gusts, precipitation, and species susceptibility. Also, a damage risk class was included to account for region (west side of the LEF experiences less damage than east), aspect (a recent storm showed less damage on north and west aspects), and elevation (the higher the elevation, the lower the damage). Finally, a species susceptibility factor was assigned to account for individual species' resistance to hurricanes. Hurricane simulations were run, and higher tree damage occurred in more intense storms in a higher risk class location for more susceptible species, and vice versa.

FACET formerly only included a species' response to drought. To account for the wet conditions of the LEF, parabolas were calculated based on individual species preferences for wet- and dry-days. However, soil moisture was too variable in FACET, so the parabolas were widened. Further work will address the model's sensitivity to soil moisture. Also, landslides may be added to FACET in the future.

Five terrain factors were selected: slope, elevation, aspect, soil type, and hurricane risk class. These factors were calculated for the entire LEF using GIS files. Three of these files (slope, elevation, and aspect) were previously available. A GIS soils file was obtained that contained combined soil series called mapping units. These mapping units were broken down into individual soil series based on slope. However, they were then combined based on similar characteristics to reduce the number of FACET simulation runs and SEMAPAR calculations. Since the individual soil series file exists, it can be used in the future for individual soil information or different terrain combinations. Finally, a hurricane risk class GIS file was created based on elevation, aspect, and region.

Terrain types for the LEF are combinations of the above mentioned GIS factors of slope, elevation, aspect, soil, and hurricane risk class. To make the number of FACET simulation runs and SEMAPAR calculations more manageable, each factor was divided into categories. Two hundred and eighty terrain types were defined using eight elevation categories, seven soil types, and five hurricane risk classes. Slope and aspect were maintained constant at 20% and 90 degrees respectively.

Resulting cover type classification was based on the four forest types (Tabonuco, Colorado, Dwarf, and Palm) plus an additional Adaptive forest type. Sixteen MOSAIC states were defined by three canopy heights and forest type corresponding to the dominant species (by basal area). MOSAIC is a semi-Markovian transition model (Dr. Miguel Acevedo, University of North Texas, Department of Geography, Denton, TX, 76203). A future improvement is to assign a different canopy height to each forest type as the forest type species grow to varying heights.

Two major comparisons of FACET simulation results were performed. The first was for long-term distributions of representative species along an elevation gradient. The second was for stand composition (given by dominant species) for representative elevations. Comparisons were made to a recent study along the Quebrada Sonadora. Also, successional patterns were analyzed for representative species of each forest type at elevations typical of this forest type. These comparisons and analyses were performed using basal area for various hurricane risk classes. Long-term basal area for representative species overestimate the recent study data for low hurricane risk, but are closer for higher hurricane risks. Therefore, FACET's results are closer to observed data as the recent study was conducted in areas that are hurricane risk class 2 and 3. Upper and lower elevation ranges for each species are close to the recent study except that *Tabebuia rigida* was not found in the recent study above 900 meters.

For the stand composition comparison, FACET overestimates basal area for some species and underestimates basal area for others. The overestimation of representative species (*Dacryodes excelsa* and *Cyrilla racemiflora*) is reduced for hurricane risk classes 2 and 3, where the recent study occurred. Conversely, *Prestoea montana* is underestimated by FACET and therefore future work is required to improve the parameter values for this species.

No data are available to compare simulated and observed successional patterns. Given the shade tolerance and growth rates assigned to each species, the results are as expected for each forest type. Also, the effect of hurricanes successfully shows the least susceptible species (such as palm) with the least negative effects on basal area, and shade-intolerant species positively affected by hurricane-generated gaps.

Several type of results were analyzed for the MOSAIC simulation. One corresponds to long-term maps for mature states, which were selected according to tree height for the different forest types. From these maps, it appears that Colorado and Tabonuco forests are dominating at proper elevation ranges, but Adaptive forests seem to be dominating areas of the Dwarf forest elevation range. Also, Palm forests are not as abundant as the literature indicates they should be.

The next type of results is from transition patterns represented by MOSAIC transition matrices calculated by SEMAPAR. Transition patterns were examined at three elevations representative of forest types at 350, 750, and 1050 meters. Two hurricanes risk classes were analyzed for 350 and 750 meters, but only one risk class at 1050 meters because there is generally not high hurricane risk at higher elevations. At 350 meters and low hurricane risk, there is a successional sequence from low to medium to high tabonuco, as expected. At the same elevation and higher hurricane risk, the sequence stops at medium tabonuco and there is medium Palm and medium Adaptive states resulting from the hurricane disturbance. There is a successional sequence from low to medium Colorado for both low and high hurricane risk. However, for high risk, there are transitions from medium Colorado to medium Adaptive. At 1050 meters of elevation, there is a successional sequence from low to medium Dwarf, but there is also a sequence from low to medium adaptive. So the effect is a mix of medium Dwarf and medium Adaptive.

Comparisons of percent cover produced by MOSAIC and FACET were performed for 350, 750, and 1050 meters of elevation for the most common hurricane risk class at each elevation. The results show a comparable match, especially for medium Colorado cover type at 750 meters. At 1050 meters, MOSAIC tracks FACET well for the early part of the simulation, but smooths out the large fluctuations in the later part.

For the sake of brevity, not all simulation years are shown for the successional maps. Years 100, 300, 500, and 700 were selected for the same set of states used for the long-term maps. Tabonuco's long-term distribution is established mid-way through the 1,000 year run. The Colorado forest type distribution establishes in the early part of the run from mid- to high- elevations. Low Dwarf distribution is limited to high elevations and establishes itself before mid-way through the 1,000 year run. Medium Adaptive also shows higher values at higher elevations as discussed before and this pattern is established before mid-way in the run. High Palm shows up after mid-way through the run and is scattered too sparsely.

Overall, this thesis accomplished its main objectives. FACET was successfully parameterized, adapted, and extended for the LEF. Likewise, MOSAIC was parameterized by scaling-up from FACET and landscape simulations were conducted. The thesis has demonstrated the enhanced capabilities of the scaling-up approach. Further work is required for improved performance of both models.

APPENDIX

Appendix 1 Soil Field Capacity & Wilting Point for Each Soil Series

Soil Series and Layer Description	Sand %	Clay %	Silt %	Field Capacity (cm^3 H_20/ cm^3 soil)	Wilting Point (cm^3 H_20/ cm^3 soil)	Layer Depth (cm)	Layer Field Capacity	Layer Wilting Point
Ciales[1]								
Mucky clay loam/clay	34	28	38	0.30	0.16	23.00	6.84	3.62
Clay loam	53	29	18	0.27	0.17	17.00	4.63	2.86
Clay loam	52	30	19	0.28	0.17	24.00	6.65	4.10
Clay loam	64	14	22	0.21	0.11	27.00	5.66	2.88
Gravelly sandy loam	60	11	29	0.21	0.09	19.00	3.95	1.77
Clay loam	43	15	43	0.25	0.11	33.00	8.13	3.53
None	71	5	24	0.17	0.07	42.00	7.09	2.73
None	55	9	36	0.21	0.09	42.00	8.93	3.61
Dwarf[1]								
Muck	70	6.6	23	0.18	0.07	9.00	1.59	0.66
Mucky sandy loam	70	6.6	23	0.36	0.18	15.00	2.65	1.10
Silt loam	8	33	59	0.41	0.25	16.00	5.75	2.93
Silty clay loam	5	43	52	0.43	0.26	27.00	11.17	6.62
Silty clay	8	46	47	0.32	0.16	22.00	9.35	5.75
Clay loam	26	29	45	0.33	0.15	21.00	6.67	3.44
Silt loam	3	27	71	0.33	0.15	23.00	7.61	3.39
Silty clay loam	6	28	67	0.18	0.07	20.00	6.68	3.05
Humatas[1]								
Silty clay	3	46	50	0.43	0.27	1.00	0.43	0.27
Silty clay	5	46	49	0.43	0.26	6.00	2.56	1.57
Silty clay	7	45	48	0.42	0.26	10.00	4.25	2.60
Silty clay	6	49	45	0.44	0.28	13.00	5.78	3.69
Clay	10	47	43	0.43	0.27	23.00	9.89	6.20
Clay	17	40	43	0.38	0.22	20.00	7.65	4.46
Clay	22	29	49	0.32	0.16	24.00	7.78	3.92
Clay	26	22	53	0.29	0.13	57.00	16.56	7.33
None	19	25	56	0.31	0.14	36.00	11.24	5.16
Los Guineos[1]								
Clay	4	80	16	0.59	0.47	3.00	1.77	1.42
Clay	3	84	13	0.61	0.50	5.00	3.04	2.49
Clay	3	83	14	0.61	0.49	15.00	9.08	7.38
Clay	3	80	17	0.59	0.48	22.00	13.05	10.48
Clay	9	56	35	0.48	0.33	35.00	16.86	11.66
Clay	16	43	41	0.40	0.24	30.00	12.01	7.30
Clay loam	13	36	51	0.37	0.20	45.00	16.59	9.00
None	28	22	50	0.29	0.13	32.00	9.18	4.13
None	30	18	52	0.27	0.12	50.00	13.67	5.76
Moteado[1]								
Cobbly clay	33	47	20	0.39	0.26	13.00	5.02	3.41
Clay	32	48	19	0.39	0.27	17.00	6.68	4.58

Clay	19	60	21	0.48	0.35	24.00	11.47	8.30
Clay	11	64	26	0.51	0.38	12.00	6.18	4.54
Clay	5	65	30	0.53	0.39	34.00	17.92	13.22
Clay	4	59	37	0.50	0.35	33.00	16.50	11.65
Palm[1]								
Very cobbly mucky silty	17	32	50	0.35	0.18	18.00	6.22	3.23
Cobbly mucky clay loam	26	33	41	0.33	0.18	23.00	7.67	4.20
Very cobbly clay loam	22	36	43	0.36	0.20	31.00	11.02	6.18
Very cobbly clay loam	19	38	43	0.37	0.21	72.00	26.43	15.04
Picacho[1]								
Sandy loam	67	19	14	0.22	0.12	3.00	0.65	0.37
Sandy clay loam	66	20	14	0.22	0.13	15.00	3.37	1.97
Sandy clay loam	64	21	15	0.23	0.13	12.00	2.73	1.59
Sandy clay loam	62	23	16	0.24	0.14	30.00	7.13	4.22
Gravelly loam/sandy	62	15	24	0.21	0.11	85.00	18.11	9.12
Utuado[1]								
Sandy loam	62	17	21	0.22	0.12	3.00	0.66	0.35
Sandy loam	63	17	20	0.22	0.12	12.00	2.62	1.41
Sandy loam	65	15	20	0.21	0.11	15.00	3.14	1.65
Sandy loam/loamy sand	73	3	24	0.16	0.06	39.00	6.22	2.18
Loamy sand saprolite	79	2	19	0.14	0.05	58.00	8.28	2.84
Yunque[1]								
Cobbly clay	3	75	22	0.58	0.45	12.00	6.90	5.43
Clay	3	76	22	0.58	0.45	26.00	14.97	11.77
Clay	3	63	34	0.52	0.38	34.00	17.64	12.81
Clay loam	8	44	48	0.42	0.25	8.00	3.35	2.03
Clay loam	13	37	50	0.37	0.21	44.00	16.48	9.10
Clay loam	15	34	51	0.35	0.19	26.00	9.19	4.82
Zarzal[1]								
Cobbly clay	20	50	30	0.43	0.29	2.00	0.86	0.57
Clay	11	64	24	0.52	0.38	15.00	7.76	5.73
Clay	11	65	24	0.52	0.39	21.00	10.97	8.16
Clay	13	65	23	0.52	0.38	27.00	13.97	10.38
Clay/bouldery clay	17	59	24	0.48	0.34	24.00	11.53	8.27
Bouldery clay	26	44	30	0.39	0.25	29.00	11.20	7.15
Bouldery clay	27	37	36	0.35	0.21	25.00	8.77	5.13
None	18	33	49	0.34	0.18	32.00	11.03	5.78
None	27	31	42	0.32	0.17	15.00	4.87	2.61
None	29	27	44	0.30	0.15	19.00	5.76	2.90
None	32	30	39	0.31	0.17	21.00	6.49	3.48
Cristal[2]								
N/A	10	64	27	0.52	0.38	10.00	5.20	3.80
N/A	9	64	27	0.52	0.38	10.00	5.20	3.80
N/A	8	64	27	0.52	0.39	10.00	5.20	3.90
N/A	8	65	27	0.53	0.39	10.00	5.30	3.90
N/A	8	65	27	0.52	0.39	10.00	5.20	3.90
N/A	11	55	35	0.47	0.32	10.00	4.70	3.20
N/A	11	52	38	0.46	0.30	10.00	4.60	3.00
N/A	11	52	38	0.46	0.30	10.00	4.60	3.00
N/A	11	52	38	0.46	0.30	10.00	4.60	3.00

N/A	11	48	41	0.44	0.28	10.00	4.40	2.80
N/A	11	48	41	0.44	0.28	16.00	7.04	2.80
Prieto[2]	17	51	31	0.44	0.30	10.00	4.40	3.00
N/A	16	53	31	0.45	0.31	10.00	4.50	3.10
N/A	14	54	32	0.46	0.31	10.00	4.60	3.10
N/A	15	49	36	0.43	0.28	10.00	4.30	2.80
N/A	15	48	37	0.43	0.28	10.00	4.30	2.80
N/A	15	39	46	0.38	0.22	10.00	3.80	2.20
N/A	15	39	46	0.38	0.22	10.00	3.80	2.20
N/A	15	39	46	0.38	0.22	10.00	3.80	2.20
N/A	15	39	46	0.38	0.22	10.00	3.80	2.20
N/A	15	39	46	0.38	0.22	10.00	3.80	2.20
N/A	18	36	47	0.36	0.20	10.00	3.60	2.00
N/A	18	36	47	0.36	0.20	10.00	3.60	2.00
N/A	11	37	51	0.38	0.21	5.00	1.90	1.05
Coloso[2]								
N/A	27	42	31	0.38	0.24	10.00	3.80	2.40
N/A	25	44	31	0.39	0.25	10.00	3.90	2.50
N/A	25	43	32	0.38	0.24	10.00	3.80	2.40
N/A	23	45	32	0.40	0.25	10.00	4.00	2.50
N/A	21	46	32	0.41	0.26	10.00	4.10	2.60
N/A	20	46	34	0.41	0.26	10.00	4.10	2.60
N/A	19	46	35	0.41	0.26	10.00	4.10	2.60
N/A	20	46	34	0.41	0.26	10.00	4.10	2.60
N/A	20	46	34	0.41	0.26	10.00	4.10	2.60
N/A	20	46	34	0.41	0.26	10.00	4.10	2.60
N/A	22	40	38	0.37	0.22	10.00	3.70	2.20
N/A	22	40	38	0.37	0.22	10.00	3.70	2.20
Cagaubo[3]								
gravelly clay loam	32	30	38	0.31	0.17	7.60	2.36	1.29
gravelly clay loam	32	30	38	0.31	0.17	10.40	3.22	1.77
very gravelly clay loam	32	30	38	0.31	0.17	10.00	3.10	1.70
Guayabota[3]								
silty clay loam	5	35	59	0.37	0.20	2.50	0.93	0.50
silty clay loam	5	35	59	0.37	0.20	7.50	2.78	1.50
silty clay loam	5	35	59	0.37	0.20	13.00	4.81	2.60
silty clay loam	5	35	59	0.37	0.20	13.00	4.81	2.60
Mucara[3]								
clay loam	32	30	38	0.31	0.17	2.50	0.78	0.43
clay	11	60	29	0.49	0.35	7.50	3.68	2.63
clay	11	60	29	0.49	0.35	15.00	7.35	5.25
clay	11	60	29	0.49	0.35	16.00	7.84	5.60
clay	11	60	29	0.49	0.35	12.00	5.88	4.20
Plata[3]	32	30	38	0.31	0.17	13.00	4.03	2.21
stony clay loam	11	60	29	0.49	0.35	30.00	14.70	10.50
clay	11	60	29	0.49	0.35	46.00	22.54	16.10
clay	11	60	29	0.49	0.35	63.00	30.87	22.05
very stony clay	32	30	38	0.31	0.17	13.00	4.03	2.21

[1]Huffaker, 1991.
[2]Soil Survey Staff, June 1995.
[3]Estimates based on information found in Huffaker, 1991.

REFERENCE LIST

Acevedo, M. 2001. Geography 5400 Environmental Modeling Course Website. Accessed November 14, 2001, and July 8, 2002. *Simulation of Environmental and Ecological Models.* http://www.geog.unt.edu/~acevedo/courses/5400/index.htm

Acevedo, M.F. Urban, D.L. and Ablan, M. 1995. Transition and gap models of forest dynamics. *Ecological Applications.* 5(4): 1040-1055.

Acevedo, M.F. Urban, D.L. and Shugart, H.H. 1996. Models of Forest Dynamics based on roles of tree species. *Ecological Modelling,* 87/1-3:267-284.

Acevedo, M.F. Ablan, M., Urban, D.L., and Pamarti, S. 2001a. Estimating parameters of forest patch transition models from gap models. *Environmental Modeling and Software*. 16: 649-658.

Acevedo, M. Pamarti, S. Ablan, M. Urban, D.L. and Mikler, A. 2001b. Modeling Forest Landscapes: Mosaic parameter estimation from gap models over heterogeneous terrain. *Simulation.* 75(5): 303-317.

Aide, T. M. Zimmerman, J. K. Rosario, M. Marcano, H. 1996. Forest Recovery in Abandoned Cattle Pastures Along an Elevational Gradient in Northeastern Puerto Rico. 28(4a): 537-548.

Barbour, M. G. Burk, J. H. Pitts, W. D. Gilliam, F. S. and Schwartz, M. W. 1998. *Terrestrial Plant Ecology*. Benjamin/Cummings.

Bonan, G.B. 1989. A Computer Model of the Solar Radiation, Soil Moisture, and Soil Thermal Regimes in Boreal Forests. *Ecological Modelling*. 45: 275 – 306.

Boose, E. R. Foster, D. R. and Fluet, M. 1994. Hurricane Impacts to Tropical and Temperate Forest Landscapes. *Ecological Monographs*. 64(4): 369 – 400.

Christopherson, R. W. 2000. Geosystems. Prentice-Hall, Inc.

Cox, S. B. 1999. Soil Properties and Microbial Functional Diversity of Surface Soils in the Luquillo Experimental Forest of Puerto Rico. Dissertation. Texas Tech University.

Doyle T.W. 1982. A description of FORICO, a tropical Gap Dynamics Model of the Lower Montane Rain Forest of Puerto Rico. Oak Ridge Pub No. 1875. 50 pp.

Delgado L. 2000. *Modelos de simulación a diferentes escalas de la dinámica del bosque tropical. Reserva Forestal Imataca. Sector Central.* MS Thesis Environmental Science. Universidad Nacional Experimental de Guayana (UNEG). 179 pp. Puerto Ordaz, Venezuela.

Everham III, E. M. 1996. Hurricane Disturbance and Recovery: An empirical and Simulation Study of Vegetation Dynamics in the Luquillo Experimental Forest, Puerto Rico. PhD Thesis. State University of New York.

Francis, J. K. and Gillespie, A. J. R. 1993. Relating Gust Speed to Tree Damage in Hurricane Hugo, 1989. *Journal of Arboriculture*. 19(6).

Garcia, A.R. Warner, G.S. Scatena, F. and Civco, D.L. 2002. Bisley Rainfall and Throughfall Rainfall, Runoff and Elevation Relationships in the Luquillo mountains of Puerto Rico. Caribbean Journal of Science. 2002 (In press).

Published as Scientific Contribution No. 1642 of the Storrs Agricultural Experiment Station.
Holcomb S. 2001. An examination of the riparian bottomland forest in North Central Texas through ecology, history, field study, and computer simulation. MS Thesis University of North Texas.
Huffaker, L. 1991. *Soil Survey of the Caribbean National & Luquillo Experimental Forests*. United States Department of Agriculture Forest Service, Southern Forest, Experiment Station.
Little, Jr. E. L. and Wadsworth, F. H. 1964. *Common Trees of Puerto Rico and the Virgin Islands*. USDA.
Long Term Ecological Research (LTER) site. 2001. Accessed December 6. http://lternet.edu/
LEF, LTER 2000. Long-Term Ecological Research on the Luquillo Experimental Forest III. NSF Proposal Number 0080538.
Lugo, A. E. and Scatena, F. N. 1996. Background and Catastrophic Tree Mortality in Tropical Moist, Wet, and Rain Forests. *Biotropica*. 28(4a): 585-599.
Lugo, A. E. and Scatena, F. N. 1995. Ecosystem-Level Properties of the Luquillo Experimental Forest with Emphasis on the Tabonuco Forest. *Tropical Forests: Management and Ecology*. Springer-Verlag New York.
Luquillo Experimental Forest Website. Site Description. Accessed June 26, 2001. http://sunites.upr.clu.edu/sunceer/aboutluq/LEFSiteDescription.htm
Luquillo Experimental Forest Website. Temperature data. Accessed June 26, 2001. http://sunites.upr.clu.edu/sunceer/DATA/lterdb16/data/ppttempsumavg.txt
Luquillo Experimental Forest Website. Precipitation data. Accessed June 26, 2001. http://sunites.upr.clu.edu/sunceer/DATA/lterdb16/data/ppttempsumavg.txt
Luquillo Experimental Forest Website. Lapse rate. Accessed September 25, 2001. http://sunites.upr.clu.edu/sunceer/aboutluq/LEFSiteDescription.htm
Luquillo Experimental Forest Website. Solar radiation. Accessed September 6, 2001. “Glob Rad” column, units = w/m2. http://sunites.upr.clu.edu/sunceer/DATA/lterdb90/data/daily/bismetday98-00.txt
Monticino, M.G. Cogdill, T. and Acevedo M.F. 2002. Cell Interaction in Semi-Markov Forest Landscape Models. pp 227-232. In: Rizzoli A.E. and A.J. Jakeman (Eds.). *Integrated Assessment and Decision Support*, Proceedings of the First Biennial Meeting of the International Environmental Modelling and Software Society. Lugano Switzerland.
National Solar Radiation Data Base Website. San Juan data. Column “AVGLO”. 1961-1990. Accessed on August 28, 2001. http://rredc.nrel.gov/solar/old_data/nsrdb/dsf/data/11641.txt
Nikolov, N. T. Zeller, K. F. 1992. A solar radiation algorithm for ecosystem dynamic models. *Ecological Modelling*. 61: 149 – 168.
Pulliam, W. and Parton, W. 1998. ZELIG and CENTURY for LEF. Poster presented at Luquillo LTER Annual Meeting, Guajataca, Puerto Rico.
Scatena, F. N. Moya, S. Estrada, C. and Chinea, J. D. 1996. The First Five Years in the Reorganization of Aboveground Biomass and Nutrient Use Following Hurricane

Hugo in the Bisley Experimental Watersheds, Luquillo Experimental Forest, Puerto Rico. *Biotropica*. 28(4a): 424 – 440.
Schellekens, J. Bruijnzeel, L. A. Scatena, F. N. Bink, N. J. and Holwerda, F. August, 2000. Evaporation from a Tropical Rain Forest, Luquillo Experimental Forest, Eastern Puerto Rico. *Water Resources Research*. 36(8): 2183 – 2196.
Schellekens, J. 2000. Hydrological Processes in a Humid Tropical Rain Forest: A Combined Experimental and Modelling Approach. Doctoral Thesis. Vrije Universiteit Amsterdam.
Silver, W. L. Scatena, F. Johnson, A. H. Siccama, T. G. Watt, F. 1996. At What Temporal Scales Does Disturbance Affect Belowground Nutrient Pools? *Biotropica*. 28(4a): 441-457.
Soil Survey Staff. 1995. Order 1 Soil Survey of the Luquillo Long-Term Ecological Research Grid, Puerto Rico. USDA, NRCS.
Thomlinson, J. R. Serrano, M. I. Del M. Lopez, T. Aide, T. M. Zimmerman, J. K. 1996. Land-Use Dynamics in a Post-Agricultural Puerto Rican Landscape (1936-1988). *Biotropica*. 28(4a): 525-536.
Urban, D.L., Bonan, G.B., Smith, T.M. and Shugart, H.H. 1991. Spatial applications of gap models. *Forest Ecology and Management*, 42:95-110.
Urban, D.L. and Shugart, H.H. 1992. Individual-based models of forest succession. In *Plant Succession: Theory and Prediction*, eds Glenn-Lewin, D.C., Peet, R.K. and Veblen, T.T. pp 249-292. Chapman and Hall, London.
USDA Forest Service – Southern Region Caribbean National Forest Website. Accessed June, 2001. http://www.southernregion.fs.fed.us/caribbean/resources.htm
Vogt, K. A. Vogt, D. J. Boon, P. Covich, A. Scatena, F. N. Asbjornsen, H. O'Hara, J. L. Perez, J. Siccama, T. G. Bloomfield, J. Ranciato, J. F. 1996. Litter Dynamics Along Stream, Riparian and Upslope Areas Following Hurricane Hugo, Luquillo Experimental Forest, Puerto Rico. *Biotropica*. 28(4a): 458 – 470.
Young, A. 1976. Tropical Soils and Soil Survey. Cambridge University Press.
Walker, L. R. Zarin, D. J. Fetcher, N. Myster, R. W. Johnson, A. H. 1996. Ecosystem Development and Plant Succession on Landslides in the Caribbean. *Biotropica*. 28(4a): 566-576.
Washington State University. Biological Systems Engineering. Soil Texture Triangle hydraulic properties calculator. Accessed September 5, 2001. http://www.bsyse.wsu.edu/saxton/soilwater/
Weaver, P. L. 1983. *Tree Growth and Stand Changes in the Subtropical Life Zones of the Luquillo Mountains of Puerto Rico.* United States Department of Agriculture Forest Service General Technical Report SO-190.
Zimmerman, J. K. Willig, M. R. Lawrence, R. W. Silver, W. L. 1996. Introduction: Disturbance and Caribbean Ecosystems. *Biotropica*. 28(4a): 414 – 423.
Zimmerman, J. K. Aide, T. M. Rosario, M. Serrano, M. Herrera, L. 1995. Effects of land management and a recent hurricane on forest structure and composition in

the Luquillo Experimental Forest, Puerto Rico. *Forest Ecology and Management*. 77: 65 – 76.